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Four/1983
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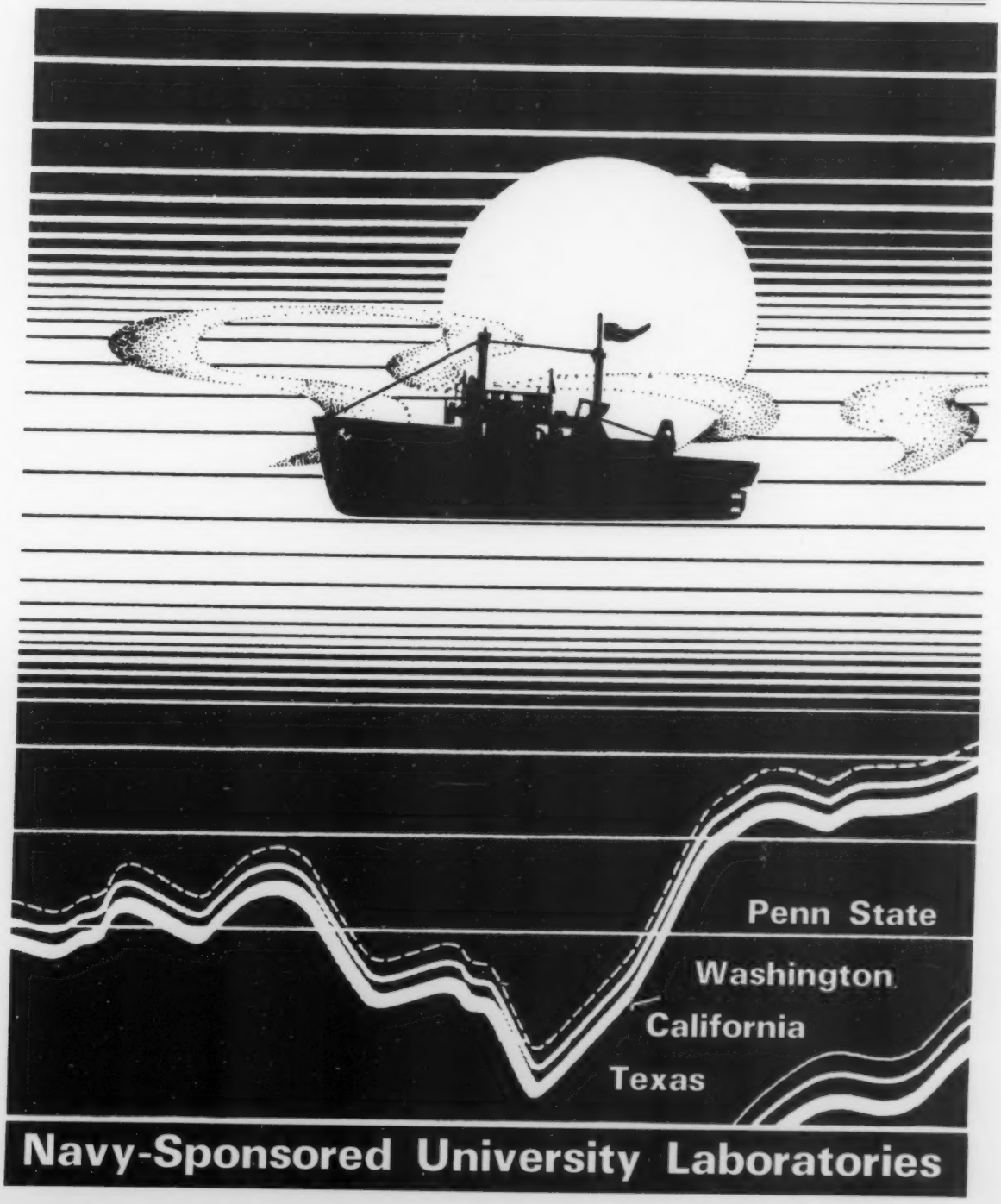
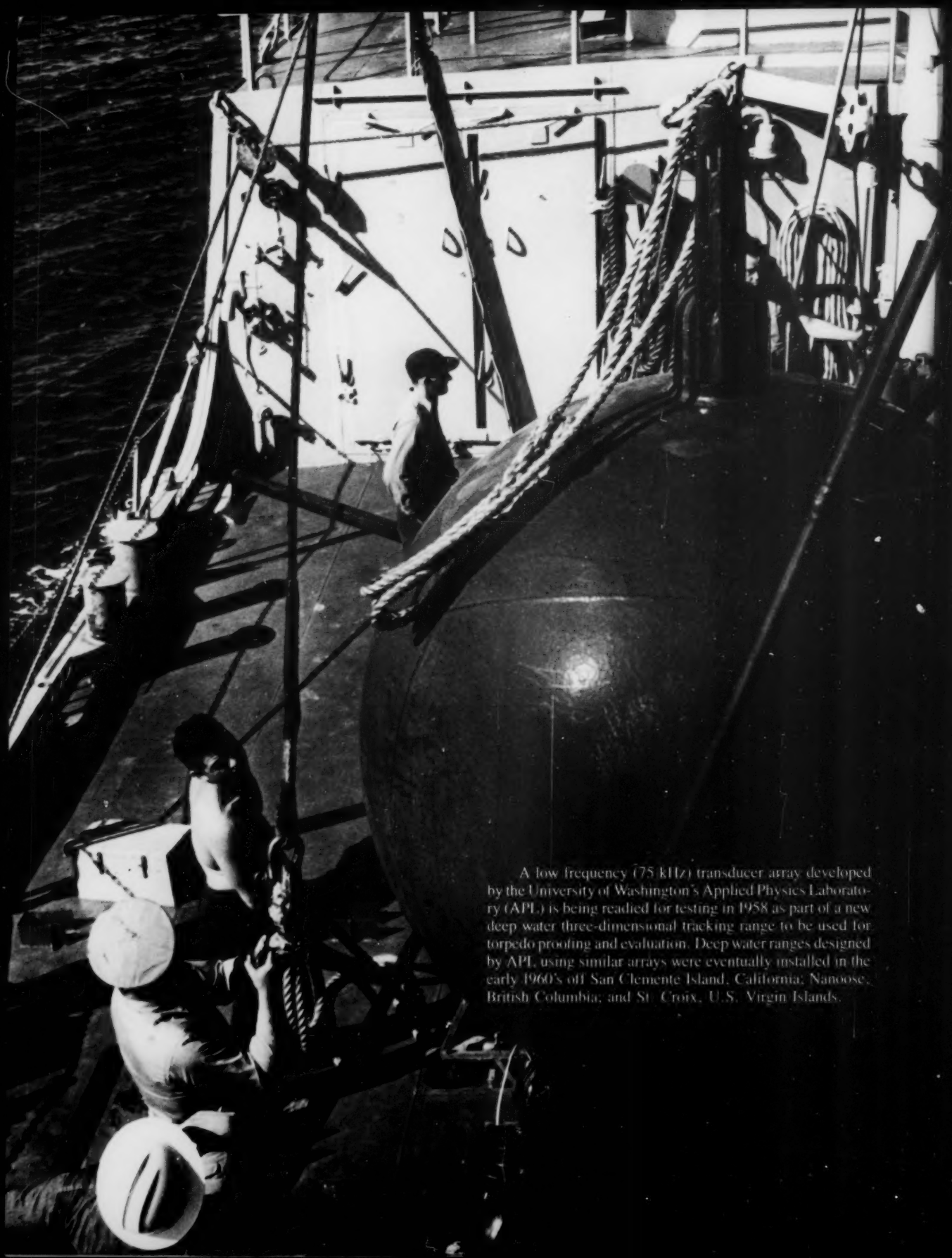


Navy-Sponsored University Laboratories



A low frequency (75 kHz) transducer array developed by the University of Washington's Applied Physics Laboratory (APL) is being readied for testing in 1958 as part of a new deep water three-dimensional tracking range to be used for torpedo proofing and evaluation. Deep water ranges designed by APL using similar arrays were eventually installed in the early 1960's off San Clemente Island, California; Nanoose, British Columbia; and St. Croix, U.S. Virgin Islands.

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About the Cover

A graphic design representing the Many-Sponsored University Laboratories, which were established during World War II for undersea warfare research at The Pennsylvania State University, the University of Washington, the University of California, and the University of Texas.

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The collective resources of the university laboratories constitute a valuable set of assets within the Navy's technology base.

Introductory Note

This issue of *Naval Research Reviews* features contributions from four university laboratories: the Applied Physics Laboratory of the University of Washington (APL/UW), the Applied Research Laboratories of The University of Texas (ARL/UT), the Applied Research Laboratory of The Pennsylvania State University (ARL/PSU), and the Marine Physical Laboratory, Scripps Institution of Oceanography, University of California, San Diego (MPL). These four university laboratories were formed in the World War II era to enlist the scientific and engineering expertise of their respective institutions for effective response to the nation's defense requirements involving undersea warfare research. The laboratories have continued as Navy-oriented research centers, specifically structured to address selected research, development, test and evaluation problems in a timely and innovative fashion.

The unique position of these laboratories, with close ties both to the Navy and their parent institutions, allows them to serve as a valuable interface between Navy technology base programs and the talent, resources, and technology available within major research universities. This connection provides an institutional framework in which academic researchers, at the forefront of emerging scientific thought and technological development, can contribute to Navy programs while maintaining their traditional academic roles. Moreover, the university laboratories' associations with academic departments involves the laboratories in training students and professionals in areas of science and technology which are of particular interest and importance to the Navy. The university laboratories differ from other academic units within their institutions in being mainly dedicated to research and development projects for Navy sponsors, with teaching as a collateral responsibility. Accordingly, the laboratories are sustained by income derived from contract sponsors and receive little or no university financial support. The Office of Naval Research (ONR) has been a major supporter of the laboratories since the 1950's.

These university laboratories differ from Navy "in-house" laboratories as well. Although formed by a long history of involvement with Navy laboratory programs, the university laboratories are characterized by the broader science and technology concerns and views of the university research community. This outlook has often led to novel and independent contributions that have served to strengthen, and to check and balance, the directions taken by Navy research and development programs. One of the most important contributory roles of university laboratory staff is serving on Navy advisory panels and special committees and providing independent expert views and recommendations on technological issues.

The collective resources of the university laboratories constitute a valuable set of assets within the Navy's technology base. The total permanent full-time staff of the laboratories is approximately 1000, of whom about one-third are faculty members. More than one-quarter of the combined professional staffs of about 500 scientists and engineers hold Ph.D. degrees. Each laboratory maintains special facilities to support Navy programs, and these facilities are augmented greatly by access to university facilities such as computer centers, libraries, research laboratories, and engineering shops. Special research facilities include stationary tanks and custom-designed barges for hydroacoustic transducer system development and testing, water tunnels for hydrodynamic research such as the Garfield Thomas Water Tunnel (48–inch diameter) at ARL/PSU, satellite monitoring stations operated by ARL/UT, MPL's unusual Research Platform FLIP, and sophisticated electronics and machine shops that specialize in converting engineering concepts into hardware for testing and modification on a timely basis. The laboratories operate or lease a wide variety of research vessels, platforms, and associated instrumentation for ocean measurements. Finally, the laboratories have a large and modern set of general and special purpose computers for use in field data collection, analysis, simulation work, and other applications.

In fiscal year 1982, Department of Defense sponsors funded the laboratories for a combined total of more than $48 million. The largest single sponsor is the Naval Sea Systems Command. The Office of Naval Research ranks second in providing contract support to the laboratories. Non-DoD sponsors also showed their recognition of the laboratories' broad areas of expertise by providing nearly $5 million, or roughly ten percent of total university laboratories funds for FY 1982.

Laboratory Directors

Dr. Kenneth M. Watson

Dr. L. Raymond Hettche

Dr. Loyd Hampton

Dr. Stanley R. Murphy

Dr. Kenneth M. Watson received a Ph.D. degree in theoretical physics from the University Iowa in 1948 and a D.Sc. degree from Indiana University in 1976. From 1957 until 1981 he was on the faculty of the University of California, Berkeley, and a staff member of the Lawrence Laboratory. Dr. Watson has served on the Air Force Scientific Advisory Board, the Defense Science Board, and the Strategic Panels of the President's Science Advisory Committee, and the National Security Council. Dr. Watson is a member of the JASON advisory group and of the National Academy of Sciences. His research in theoretical hydrodynamics has been supported through the Physical Oceanography program of the Office of Naval Research.

Dr. L. Raymond Hettche assumed the directorship of Penn State's Applied Research Laboratory in November 1981. Before coming to Penn State, Dr. Hettche, who holds M.S. and Ph.D. degrees in civil engineering from Carnegie-Mellon University, was Superintendent of the Material Science and Technology Division of the Naval Research Laboratory in Washington, D.C. He has written many papers and reports in the area of engineering mechanics and has as a particular research interest the response of materials to intensity radiation and especially to pulsed laser heating.

Loyd Hampton is Director of Applied Research Laboratories, The University of Texas at Austin. He is a Fellow in the Acoustical Society of America and has a Ph.D. in Physical Oceanography. During his thirty years at ARL/UT he has been involved in a variety of acoustics problems including early studies of acoustic reflection and scattering and currently, studies of low frequency acoustic propagation in the ocean bottom. Under ONR sponsorship, he was Editor of the 1974 publication of *Physics of Sound in Marine Sediments*.

Dr. Stanley R. Murphy joined the Applied Physics Laboratory, University of Washington (APL/UW), in 1952 and served as Assistant Director from 1965 to 1968. In 1978 he became Director of the Division of Marine Resources and the Sea Grant Program at the University of Washington. He returned to APL/UW in 1980 as Director and is Professor of Oceanography and Mechanical Engineering. His interests include underwater acoustics and ocean engineering.

More information about each of these laboratories may be obtained directly.

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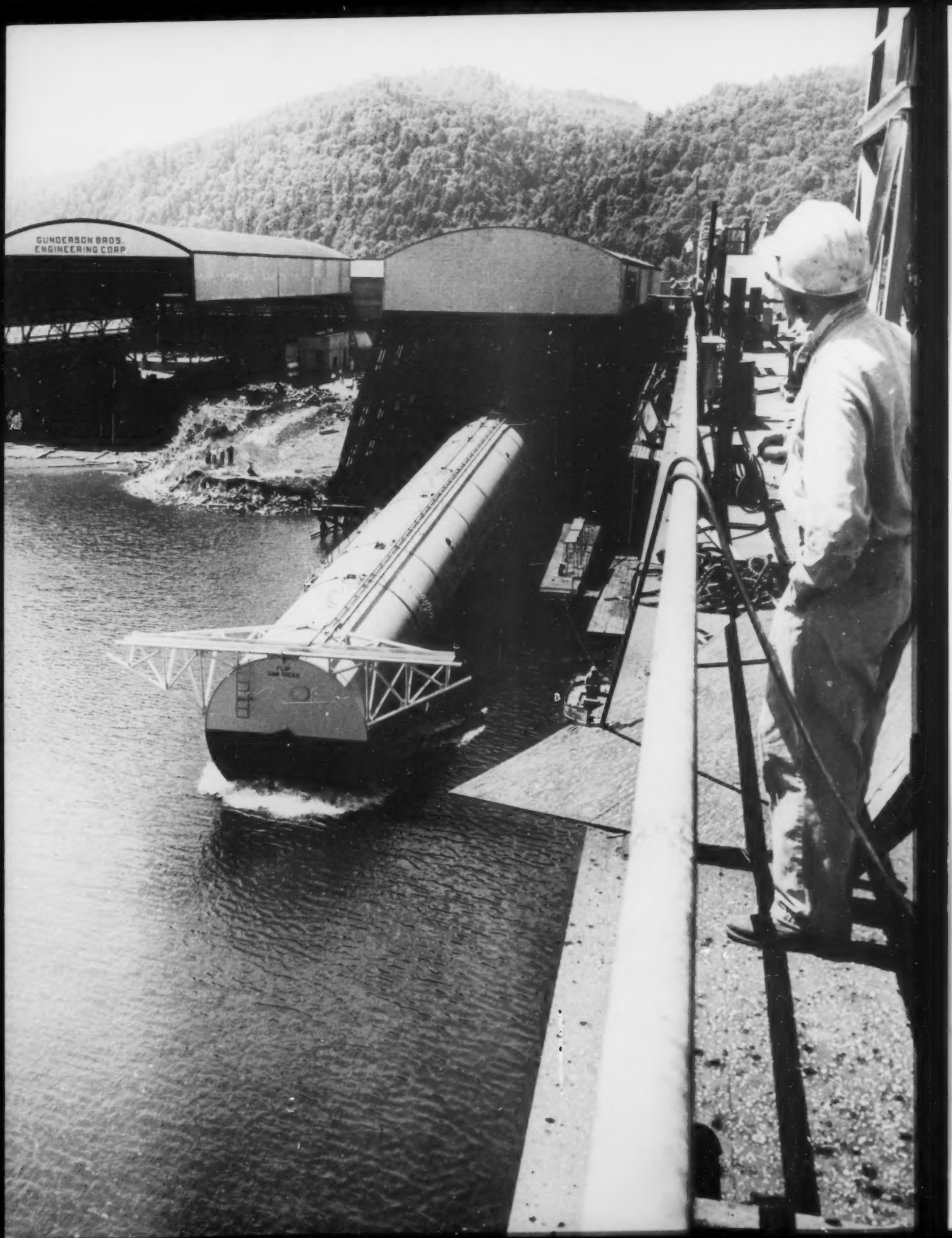
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Instrumentation and Platform Development

by

The Staff
Marine Physical Laboratory
Scripps Institution of Oceanography

Research Platform FLIP (Floating Instrument Platform)

Some devices that are used for research projects become obsolete as soon as the project that initiated their development is completed. Some find further use in work closely related to the first project. Others have inherent capabilities which make them useful for a variety of purposes which were not part of the original plans. Such a device is the Research Platform FLIP, which was built under Office of Naval Research (ONR) sponsorship in 1962 and which is operated by the Marine Physical Laboratory of Scripps Institution of Oceanography. FLIP was originally intended to be a platform from which to make accurate acoustic measurements needed by the Navy's Submarine Rocket (SUBROC) Program and has been used for many different scientific purposes during the ensuing 20 years.[1] SUBROC was to be launched using sonar information only and the Navy needed to understand how the inhomogeneities in the ocean would distort the transmission of sound. The use of operational submarines to work on this problem was tried, but it soon became apparent that they were inadequate platforms for this purpose. It was suggested to the SUBROC Technical Advisory Group (STAG) that a large spar buoy-type platform would have the necessary stability and could support the instruments required to compare the direction of arrival of underwater sound signals with their in-air electromagnetic counterparts.[2,3]

FLIP's principal feature is a hull design which when vertical, provides a low response to the motion of the sea surface in the range of wave periods most often occurring, and which when horizontal can be towed effectively. This design resulted in a cylindrical hull of 6.5 meter diameter from 91 to 49 meter depth which tapers down to 4 meters at the 20 meter depth below the vertical water line. FLIP's overall hull length is 108 meters, most of which contains ballast tanks, with working and living spaces at the bow. FLIP's vertical motion is less than 10% of wave height over most of the normal periods, rising to 18% at the 17 second period and reaching zero at 22 seconds, a wave period rarely encountered. It did happen on one long trip in the North Pacific Ocean, but FLIP survived the 25 meter waves with only some water damage to electrical circuits.[4]

Her excellent stability characteristics provide a low motion and low noise platform for scientific measurements, and make it possible for crew and scientists to live and work in relative comfort in the open ocean in most sea conditions encountered. Lab spaces house electronics instrumentation, and platforms at each of the four decks provide space for working with in-water equipment. Five crew members and eleven in the scientific party can remain at sea without support for 30 days, and even longer if food and fuel are replenished. Her longest trip has been for 45 days in the Gulf of Alaska, with 27 days in vertical.

FLIP is towed in the horizontal position to the operating area (usually at 7 to 10 knots) and upon arrival is changed to the vertical mode and placed in a 3-point moor, often in 4000 meter water depth, to serve the needs of scientists who make long term in situ measurements at sea. At other times she will drift after the towship departs, allowing measurements to be made in the moving water mass that carries her. Other ships may be in company for cooperative work, or FLIP may remain alone until time for the return tow to port. Whichever mode of operation is used, for 20 years FLIP has proven to be an effective platform for research at sea which requires measurements at a fixed position, from a stable suspension point, or in the near surface zones with minimal disturbances.

The principal field of interest has been underwater acoustics problems of Navy interest. From the initial work in mid-frequency propagation measurements at first convergent zone range, the propagation research conducted on FLIP has progressed to include both very long range, low frequency (<150 Hz) measurements which examine the acoustic stability of the ocean and its multipath structure, and short range

Launching of FLIP on June 22, 1962 into the Willamette River, Portland, Oregon. The booms at the stern were for mounting hydrophones.

examinations of stability at high (>50 kHz) frequencies. The 20-element vertical hydrophone array developed for the low frequency work proved to be so insensitive to platform and cable noise that it has provided an effective tool for studies of ambient ocean noise, particularly its vertical distribution. The ability to modify the array configuration at sea by changing hydrophone locations has made it possible to sample ocean noise distributions in situ at different depths within a short time period. The measurements are made with FLIP in a 3-point moor in water depths that are not acoustically "bottom-limited."

Another aspect of interest has involved the scattering of acoustic energy from the sea surface, and from within its volume. These measurements are conducted while FLIP drifts with the currents, using sonar transducers mounted on her hull. In one experiment, the acoustic data was correlated with biological samples collected in the sonar beam. Her 12-ton scientific payload has permitted the installation of a multi-element array of high power Doppler sonar transducers which have provided unique and detailed data for studies of the motions of internal waves in the upper layer of the ocean.

In addition to acoustics, physical oceanographers have studied the propagation of storm waves, the upper ocean current structure, variations in temperature structure, and factors affecting the optical properties of open ocean waters. FLIP has carried scientists who investigated air-sea interaction properties in both the North Pacific Ocean and as part of the BOMEX program, in the Caribbean Sea. To accommodate the variety of oceanographic instruments used in these programs, FLIP has been equipped with a set of booms, one of which can be extended as far as 75 feet from her hull. Instrument packages can be winched in and out on tracks, thus preventing entanglement with the hull or interference from hull hydrodynamic effects.

While all of this work contributes to the advancement of scientific knowledge of the oceans, applications to problems of interest to the Navy are of prime importance. The initial work on sonar bearing accuracy provided data critical to the target motion analysis which supported the SUBROC weapon system. Long range propagation measurements have provided key inputs to data banks used in acoustic models that support acoustic detection system designs. Low frequency noise investigations have provided new insights into the statistics of ocean noise that affect the performance of acoustic surveillance systems. Observations of acoustic scattering from the sea surface have provided data useful to homing weapon systems designers. Underwater acoustic and temperature measurements coupled with factors affecting the sea surface have made possible new understandings of the nature of internal waves and air-sea interactions.

Deep Tow Instrumentation System

The deeply towed survey system[5] developed by Spiess' group at MPL over the last 20 years, provides a good example of the interplay among various levels of sea floor activity—research, exploratory development and operational—spanning the full range of Navy interest. It also is an example of the philosophy of incremental expansion of system capabilities in response to research or operational needs.

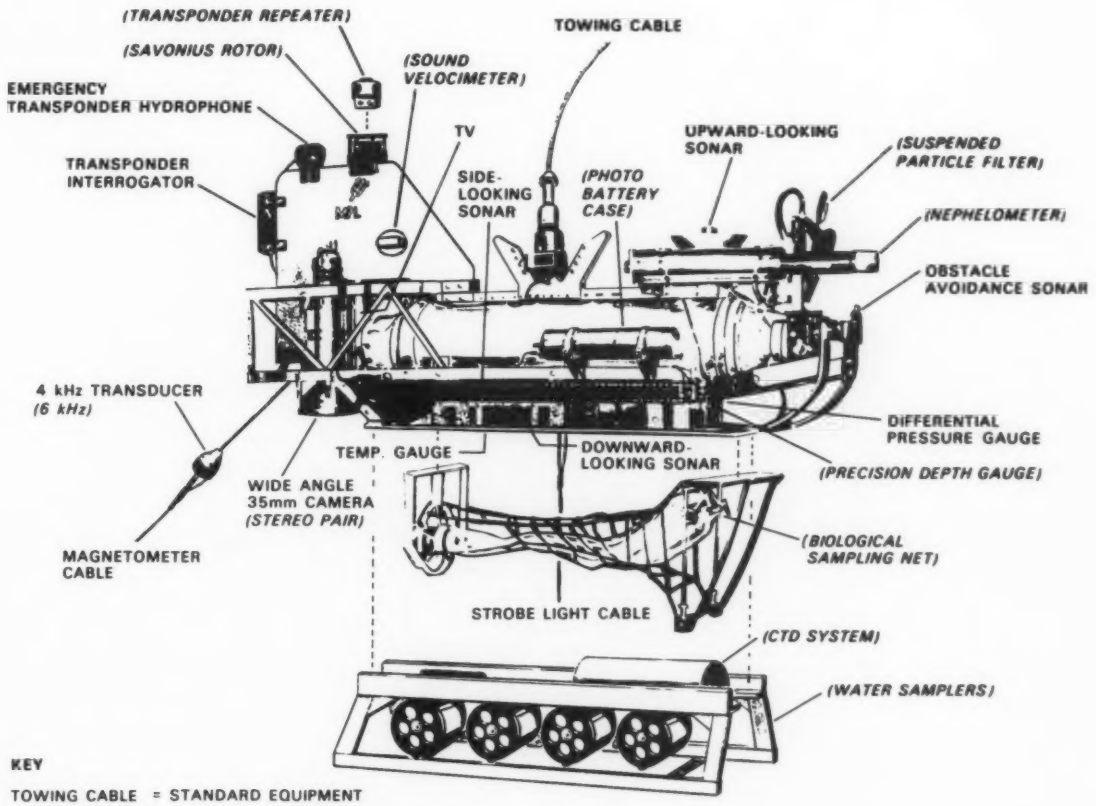
As the SUBROC program was developing in the late 50's a major environmental question emerged—how well would the direction of arrival of a sonar signal be related to the direction of an actual line of position between the sound source and receiver—the "bearing error" problem. Errors could obviously arise from refraction and, for bottom bounce paths, from reflection from a sloping sea floor. While the physical principles involved were simple, there were inadequate environmental measurements to define the magnitudes of these effects. SUBROC program funds were thus provided to build FLIP (discussed elsewhere in this article) to support studies of refractive errors, and to build a system to measure the slopes of facets of the sea floor on the appropriate scale (horizontal averaging over 50–100 meters as opposed to ordinary echo sounders having footprints one or two km across in deep water). We chose to gather data for the latter problem by building and operating a precision near-bottom echo-sounder system. We did this, however, with knowledge that other aspects of the sea floor could benefit from close scrutiny as well, and thus we allowed for future addition of other sensor systems.

From the beginning, careful tracking of the location of the towed body was essential. Slope measurement clearly implied good horizontal as well as vertical position measurement. Since the vehicle was to operate far below the sea surface at the end of a long wire (4–6 km deep with 6–9 km of wire out) we felt that a bottom referenced system would be preferable and thus developed an acoustic transponder approach, including both hardware[6,7] and software[8] which is currently capable of providing real time vehicle positions within 1–2 m and towing ship locations to about 30–50 m. Along the way we found a further need to be able to track bottom sampling equipment within the transponder net and thus developed a "relay transponder" to solve that problem.[9]

Early additions to system capability were a proton precession magnetometer (spurred by a desire to understand the nature of the lineated magnetic anomalies then being mapped at the sea surface) and side-looking sonar (motivated by interest in sea floor search capabilities following loss of Thresher in 1963).[10] These systems began to disclose unforeseen geological features and stimulated the addition of a stereo photographic system and a low frequency sounder to determine subbottom structure. The latter was designed to operate at 4 kHz in a quantitative mode to provide better information on the in situ acoustic properties of deep ocean sediments.

Figure 2

Deep Tow Instrumentation System.

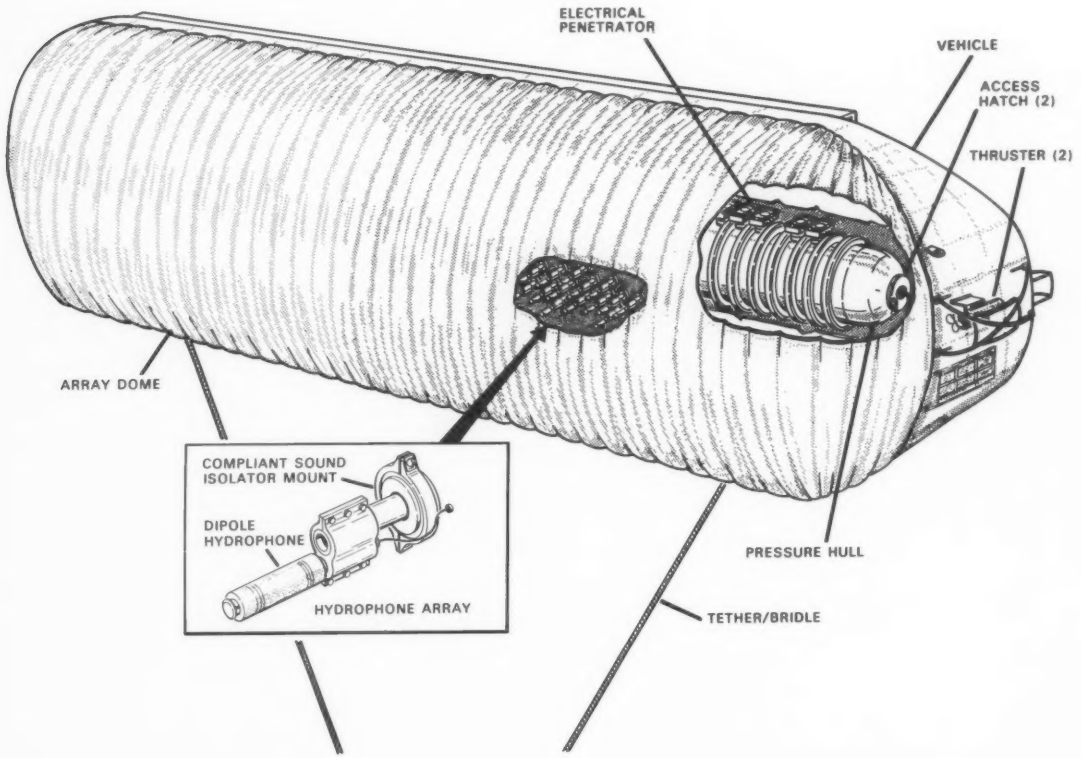


An important part of the system growth process was development of handling gear which would allow the vehicle (about one metric ton in air) to be launched and retrieved safely, with minimal manpower, in heavy seas as well as optimizing ship maneuvability while towing at low speeds (½ to 1 m/sec—1–2 kts). Prime reliance was placed on well-logging cables (usually about 9,000 m long) having a coax core capable of handling the necessary electrical power and of passing control signals down to the vehicle and sending returns from the various sensors back up.[5] Our major cable handling device is an articulated boom crane. The vehicle is locked to the end of the boom during launch and recovery, thus providing positive control. With the vehicle in the water the wire is paid out and the crane is allowed to swing as a fairlead in response to the towing wire, thus providing an effective towing point well forward of the rudder and enhancing ship control, particularly when using single screw ships (THOMAS WASHINGTON, DE STEIGUER and SILAS BENT have all been used). Cycloidal propulsion ships (R/V'S KNORR and MELVILLE) are the best for this sort of work, although the single screw ships, all with good bow thrusters, are reasonable. Smaller twin screw ships (Fay and Gyre) without continuously operable bow thrusters are only effective in fair weather.

The other handling innovation has been provision of remote control for operation of the main winch by the scientific party from the laboratory. This is the means by which the

Figure 3

Advanced Detection Array



vehicle is maintained at the desired height off bottom (usually 5 to 50 m) in the deep ocean to depths of 7,000 m.

Starting with bottom slope studies the system has grown with operational tasks ranging from finding wreckage in support of Navy missions[11] through underwater acoustic investigations,[12] studies of sea floor sediment bedforms[13] extensive investigations of plate tectonic phenomena, particularly at spreading centers.[14,15,16] In the last named context the deep tow has been a particularly valuable system in providing the fine scale setting within which submersible operations (ALVIN, CYANA, SEA CLIFF and TURTLE) can be fruitfully carried out and interpreted.[17]

At present the system includes, on a routine basis, precision echo sounder, side-looking sonar, stereo photography, proton precession magnetometer, water temperature, clarity and conductivity sensors, subbottom structure sounder and an obstacle avoidance sonar. Special systems have been developed and used when the mission has a particular need to collect water samples, filter out particulate matter from the water, make near-bottom plankton tows and, most recently, to make deep sea floor acoustic backscatter measurements at discrete frequencies over the range from 4.5 to 160 kHz.

Development of this system has been carried out largely with Navy sponsorship, starting with SUBROC and the Deep Submergence Project and maintained through the Office of Naval Research and other commands (research and explora-

tory development funding). Seagoing use has been funded primarily by the Navy and the National Science Foundation.

The system has been used at about 50 sites in the Pacific and Atlantic Oceans and the Mediterranean and Red Seas. In addition to its research and operational contributions it has played a substantial educational role. To date 19 students have completed Ph.D. degrees based in large part on deep tow data. The disciplines represented have been primarily geology and geophysics, with a few from engineering and one in biology. The ability to mix educational activities, multi-disciplinary basic research, a wide range of applied activities and a multiplicity of sponsors has kept this a lively, vital satisfying program for nearly 20 years.

Advanced Detection Array (ADA)

One of the main objectives of the ADA program at the Marine Physical Laboratory has been to observe the background statistics of the noise in the ocean as seen through a high-gain directional receiving array. Years of investigation of the ambient noise in the ocean left many questions unanswered, principally because the measurement tools were not sufficiently refined to examine the fine-scale temporal and spatial distributions of the noise. To attack this problem, Dr. Victor Anderson's group in the late 1970's developed a submersible vehicle to carry a large aperture acoustic array capable of high angular resolution of the ambient noise field.[18] This array is mounted on a submersible platform which consists of a large pressure hull containing processing and control electronics, and a supporting structure and skin which provides buoyancy for operation on the surface. The outer hull provides a planar deck to support the 720 cardioid hydrophones over a spatially tapered aperture 7 meters high by 20 meters long. The beamformer electronics racks in the pressure hull occupy ½ of its 20 meter length. All of the 720 hydrophone cables are connected to the interior electronics through 15 high pressure electrical penetrators located along the pressure hull.

A randomized truncated-Gaussian distribution of spacings was used to establish the positions of the elements within the array aperture. The average spacing varies over a factor of two-to-one from the center to the edge, being closer at the center.

The ADA vehicle is designed to be towed to sea in conjunction with its support platform ORB (Oceanographic Research Buoy) and submerged to depths as great as 1200 meters. ORB has no propulsion system, so therefore must be towed to and from the operating area along with ADA. The handling and mooring system configuration of ORB and ADA was designed to provide safe transport for the array vehicle and ORB from their berths to a selected operating area at sea, to place two secure moorings on-site, and to submerge ADA to its operating depth. The ADA moor leg must be pre-measured to match the water depth so that it goes in as a taut vertical moor. The ORB moor leg by contrast must have sufficient scope (moor length/water depth) to allow haul-in of the moor so as to move ORB in a direction away from the ADA moor, thereby pulling the flooded but still positively buoyant ADA array vehicle beneath the surface via tension in the umbilical.

The average power of the beams from ADA is transmitted over an umbilical telemetry link to the surface support platform ORB for further processing, recording and analysis. In order to protect the 3 cm cable, it passes through a towing horn which is contoured to a 1.2 meter radius to avoid over-stressing the cable. It is lined with high-density polyethylene to minimize abrasion of the galvanized armor wires. ADA is trimmed to a positive buoyancy of 2000 to 5000 kg when submerged for fail safe operation in the event of the loss of the umbilical cable.

After being calibrated acoustically, the array was used on several expeditions to investigate both fine-scale aspects of ambient noise and detection performance against submarine targets. The results have provided detailed data on the horizontal and vertical distributions of noise, and on its statistical properties which are susceptible to advanced signal processing methods.[19] The detection performance potential of a large aperture mid-frequency acoustic array also has been described.[20]

Support for the ADA program came from several agencies. The Defense Advanced Research Projects Agency supported the design and construction of the array system. The Office of Naval Research and the Naval Sea Systems Command joined DARPA in the support of air-sea measurements and data analysis.

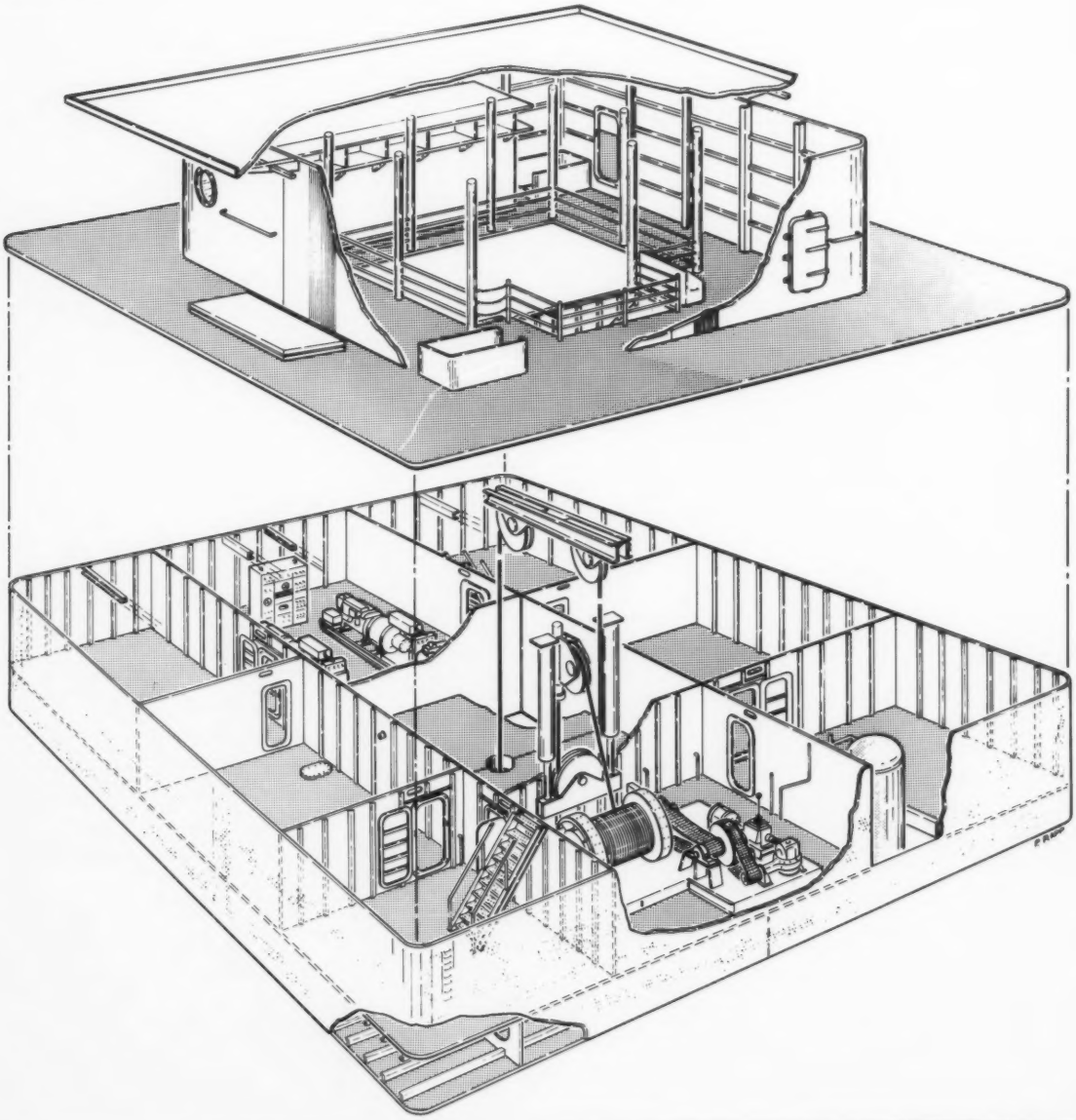
Research Platform ORB (Oceanographic Research Buoy)

ORB, a 21 × 14 meter rectangular shaped vessel displacing approximately 330 tons, was developed by Dr. Victor Anderson's group at the Marine Physical Laboratory in 1967 to serve Navy supported projects at the laboratory which require the launch, retrieval, implantation or handling of large equipment or systems in the open ocean. Its original use was as the support platform for RUM (Remote Underwater Manipulator); a 12-ton remotely controlled, unmanned, bottom crawling vehicle with a manipulator arm, optical and acoustic sensors.[21] The flexibility of ORB's design has enabled it to act as an effective platform for acoustic transmitters, receivers, transducers and hydrophone arrays, not only for studying ambient noise and reverberation, but also for testing underwater components. Its capabilities were modified to support ADA (Advanced Detection Array), described above.

The ORB fabrication was funded by ONR. The original design requirements were low cost, plenty of A.C. electrical

Figure 4

Three dimensional view of ORB (Oceanographic Research Buoy).



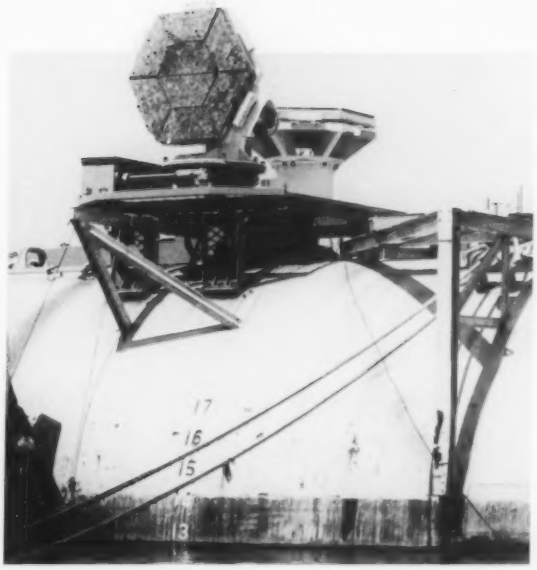
power, living space for six crew members and six scientists, a good winch and surge accumulator system for the main cable, and a center well for handling equipment. These objectives were achieved by a simple box structure with living quarters, lab and machinery spaces symmetrically arranged around a center well. The center well is a 4.5 × 6 meter area, which when opened simplifies the tasks of placing and retrieving objects in the ocean. The well doors when closed provide a dry work space and will safely support a weight of 12,000 kg. Loads up to 12 tons can be lowered to a maximum depth of 2,000 meters. They are safely handled with a system that includes a number of automatic control features. The supporting cable also serves simultaneously to transmit as much as 30 kilowatts of power and all necessary control signals to the remote equipment, and to return from it a variety of data, including television video signals. Air cylinders with a larger air reservoir are used for the accumulator system. The box construction and essentially flat bottom damps the rapid 2 second roll/pitch period of ORB so that it essentially follows the sea surface for wavelengths greater than 30 meters and filters the smaller chop.

ORB is 8 meters high from keel to upper deck. It has no means of self-propulsion and must be towed to and from operating areas, usually at 5 knots. The vessel is equipped with diesel generating sets which provide up to 240 kilowatts of electrical power. ORB's equipment also includes the necessary navigation aids, communication and safety equipment. It can carry sufficient fuel and water for a stay of up to 30 days while moored on station. Personnel rotation and provisioning at sea have been accomplished by a small boat. In addition to laboratory work spaces and machinery space, ORB is equipped with complete living facilities for 20 people including five crew members.

During her first 11 years of operations, ORB has been moored at over 20 sites ranging up to 400 km off the southern California coast and at depths from 30 to over 4,000 meters, providing a stable and sheltered platform for over a dozen different projects.[21] These include benthic biology experiments with RUM, large scale midwater acoustic array measurements with ADA, shallow water parametric sonar scattering studies, deep water concrete structure inspections, expendable sound source tests, and sonar experiments with USS DOLPHIN (AGSS–555).

Doppler Sonar

For the last fifteen years an ONR-supported program has existed at the Marine Physical Laboratory to study internal waves and other small scale motions in the upper ocean. Dr. Robert Pinkel's group has used the research platform FLIP as a stable mount, from which arrays of sensors can be suspended. Initially temperature profiling instruments were used which reached to depths of 400 meters. Long booms were mounted on FLIP in an attempt to achieve a significant horizontal separation between three simultaneously profiling



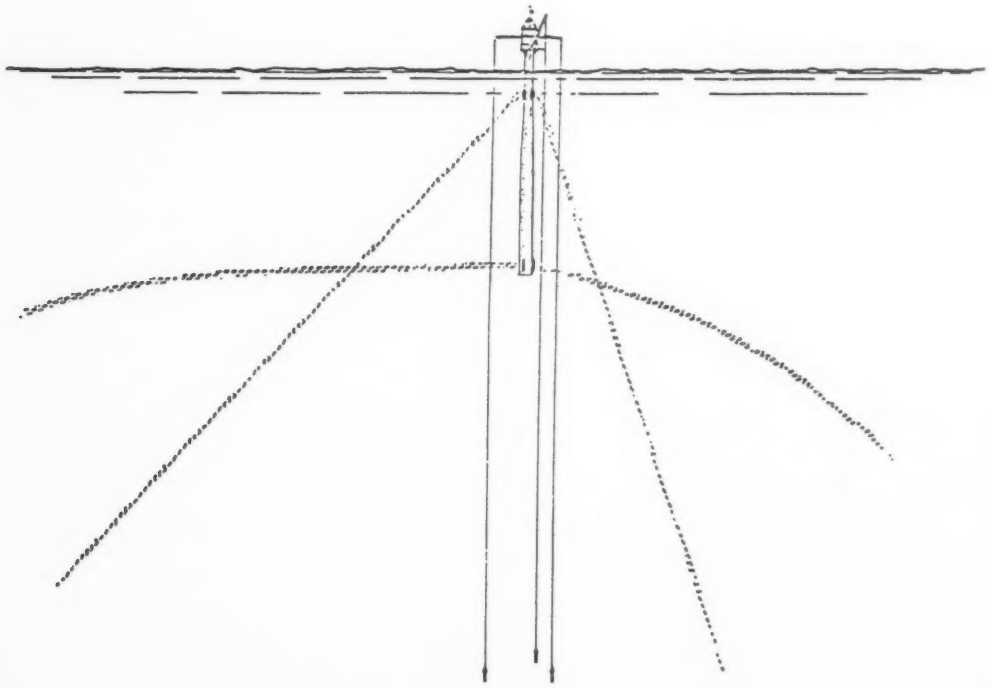
Photograph of the lower Doppler sonar installation on FLIP. When "flipped" these four sonars will be at a depth of 85 meters pointed horizontally.

sensors. The horizontal separation was necessary in order to be able to determine the direction of propagation of the waves. As typical energetic internal waves have wavelengths a kilometer long or longer, it was desired to create as large a horizontal array as possible in order to accurately measure the propagation direction. However, it proved impractical to deploy booms greater than ~.20 meters length, which limited the maximum horizontal aperture of the FLIP temperature array to 44 m. While useful directional measurements of the shorter waves resulted from even this small an array, it became clear by 1973 that a significantly larger horizontal aperture would be required to adequately understand the physics of the wavefield.

Dr. Fred Spiess, then Director of MPL, suggested that it might be possible to use Doppler sonar to achieve the large spatial aperture necessary for these studies, without the practical problems associated with a physical array. The idea was to duplicate the work then being started in the atmosphere, using both acoustic sounders and radars. Sound would be transmitted in a narrow beam, and would scatter off plankton and nekton in the sea. From the Doppler shift of the returned echo, the component of scatterer velocity parallel to the beam could be deduced at many ranges. With several sonars pointed in different directions, the required horizontal aperture could be achieved.

Figure 6

A schematic diagram of the FLIP internal wave array. Hashed lines represent the position of the acoustic beams from the four sonars. The instruments which hang beneath FLIP are profiling conductivity, temperature and depth sensors. These can measure the oceanic density field down to a depth of 400 meters.



In early 1975 work started with ONR support on the development of an oceanic Doppler sonar. The objective was to develop a system with a range of 1 km, range resolution of 20 m, a 1° beamwidth, and 1 cm/sec velocity precision. Initial tests were performed in Lake San Vicente, near San Diego, using a variety of borrowed transducers. In 1976–77 the first sea tests were conducted from FLIP using a narrow beam 87.5 kHz sonar developed by Dr. Fred Fisher of MPL. Following the success of these measurements, development was started on a special purpose Doppler sonar.

The new instrument was created in a modular fashion. A hexagonal aperture, 1.5 m diameter, was formed by assembling eight smaller hexagonal panels. Each panel consists of 210 discrete transducers. Thus, the eight-panel array consists of 1680 transducers which can be driven at a peak power of 32 kW at frequencies between 65 and 85 kHz.

Following successful tests of the first sonar design, an additional 12 modular panels were constructed. These were eventually formed into a second 8-panel sonar and two 2-panel sonars, which when mounted on FLIP were pointed in different directions, so as to create an antenna capable of determining the propagation direction of the internal waves. The two larger sonars were mounted on FLIP's stern, at a depth of 85 meters when vertical. These were directed horizontally, with beams separated by 90° in azimuth. The smaller sonars were mounted high on FLIP's hull, at a depth of 30 m, with beams angled downward 45°. The plan was to use the horizontal sonars to determine the propagation direction of small scale internal waves. The slant sonars detect the shear field in which these waves must propagate.

During April and May 1980 the four-sonar system was used at sea for the first time. Approximately 18 days of acoustic data were collected as FLIP drifted slowly southward in the California Current, approximately 400 km west of San Diego. Examples of the profiling data are presented in the accompanying figures. One figure emphasizes the close-up view of the oceanic velocity field attainable with acoustics. Profiles are separated by 30 seconds. The companion figure gives a long-term view, with hourly averaged profiles plotted. The information obtained from a single Doppler sonar is equivalent to that from a linear array of 64 current meters.

As the data are being analyzed, additional cruises are being planned. A study of large scale turbulent structures is part of ONR's mixed layered dynamic experiment (MILDEX) in late 1983. A sonar study of the equatorial undercurrent and deeper current structures is being proposed for later in this decade.

Acoustic Arrays

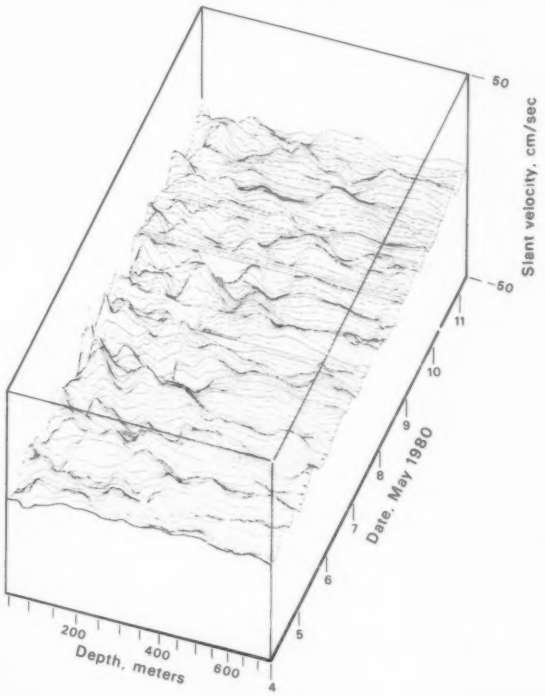
The Marine Physical Laboratory's programs in underwater acoustics have led to the development of a number of hydrophone arrays for passive reception of signals and ambient ocean noise, and of transducer arrays for signal transmission and reception. An early project in the 1950's in collaboration with the Submarine Force, U.S. Pacific Fleet, was the development and testing of a long-line, low-frequency passive array on a fleet submarine to extend detection ranges. This work was supported by the Sonar Office of the Bureau of Ships, and its results were helpful in establishing criteria for later sonar systems.

The need to measure environmental effects on sonar bearing accuracy from FLIP led to the development of a 15 meter horizontal hydrophone array mounted near her 90 meter draft to receive the signals transmitted from first convergence zone distances. This aperture provided the horizontal bearing resolution required for Dr. Fred Fisher to measure arrival angles with 0.01° accuracy, and therefore evaluate bearing accuracy and fluctuations over a 60 km convergent zone acoustic transmission path. Using three of these horizontal arrays at depths of 30, 60 and 90 meters, additional studies on bearing errors and fluctuations were conducted on surface duct and bottom bounce propagation paths, as well as investigations of internal wave effects on bearing fluctuations.

Studies of long range, low-frequency propagation in the deep ocean required the development of hydrophones which could be suspended from FLIP and be insensitive to the vibrations of the suspension cable. This was achieved by William Whitney's design of a modular shock-mounted hydrophone cage which could be easily connected to the double-lay armor-coaxial suspension wire. Twenty of these low

Figure 7

A seven day record of velocity profiles from an upper slant sonar. Profiles are separated by one hour in time. The depth axis has been rescaled to account for the depth variation in the Vaisala frequency.

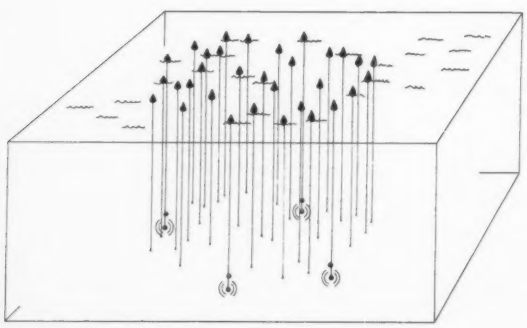


frequency hydrophone units have been used on many expeditions, deployed vertically from FLIP with variable hydrophone spacings and depths to investigate both long-range acoustic propagation and ambient sea noise. The results of this work have not only increased our understanding of these phenomena, but have provided valuable inputs to models used for surveillance system designs and performance predictions.

Microelectronic components and Kevlar fibers have made possible the design of much longer, more capable and lighter weight acoustic arrays which are entering development this year. They offer promise to extend our abilities to define the fine scale aspects of propagation and ambient noise, and thus determine further opportunities for surveillance system improvements. These arrays will be deployed both horizontally and vertically from FLIP, with groups of hydrophones feeding in-line microprocessors which will provide digitized data to the onboard signal processors. Variations in depth of the horizontal array will be provided by special arrangements in the mooring system.

Figure 8

Thirty-two element random sonobuoy array.



Dynamic Beamforming Hardware and Sonobuoy Applications

The concept of coherently summing together the sensor outputs from a random array of freely drifting sonobuoys stimulated work by Dr. Victor Anderson's group at MPL to fabricate a dynamically programmable beamformer. As conceived, the drifting sonobuoy array would be a sparse array with average element separations much larger than one-half wavelength at the frequencies of interest. The requirements imposed by this drifting, sparse array were the essence of Dynamic Beamformer design. Being a sparse array, the number of resolvable coherent combinations or beams formed from the individual sonobuoy sensor outputs would exceed by several orders of magnitude the number of elements themselves. Being a drifting array with time varying element locations, the beamforming time delays would need time to be adjusted dynamically in order to accommodate the changing geometry.

Design considerations were based on the practical aspects of implementing the beamforming process including the mathematics of time domain beamforming from an array whose elements are located arbitrarily in three-dimensional space, the number of beams which a sparse array must form to adequately probe the volume, the effects of time-delay quantization and data interpolation for time domain beamforming, and multiplexing the sensor input data and blocking the beam output data.

The Dynamic Beamformer uses a time-delay-and-sum approach to coherently combine the element signals for a particular look direction. A large number of such combinations, or beams, must be generated in real time. The number, in fact, is so large that it becomes a significant factor in the beamformer architecture design. The statistical nature of the side lobes associated with a sparse, random array also must be recognized. Additionally, an important factor in the architecture design is the degree of quantization required in the time delays of the beamforming process.

The random arrays under consideration are composed of a three-dimensional distribution of equally weighted, omnidirectional sensors. The beamforming task consists of generating the waveform for each desired steered beam direction. Time delayed replicas of the individual element signals compensate for the differential travel time differences between sensors for a signal from the desired beam direction.

The complexity of the beam formation process arises from the need to define the beamformer output in real time for a large number of beams. In the Dynamic Beamformer, 32 element data inputs are transformed into 1300 beam data outputs. A distinguishable feature of the Dynamic Beamformer is that the element positions and beam directions are treated as dynamic variables and are allowed to change slowly during the transformation process. Fluctuations in sound speed and array element locations are mapped into variations within a time-delay coordinate system.

The large number of beams formed in parallel in the Dynamic Beamformer is a consequence of its intended use to process sensor data from a sparsely filled random array, since it is the aperture of the array and not the nunber of array elements which determines how many beams are required to adequately probe large sectors of space.

A number of features have been incorporated into the Dynamic Beamformer which provide a great deal of flexibility during data analysis. Of primary significance is the capability to interact with the master controller on a real-time basis and thus alter the mode of operation. For example, the master controller issues commands to the magnetic tape recorder calling for forward, fast forward, rewind, or stop. Since this interaction can be with another computer as opposed to an operator, a closed-loop mode of data analysis is possible, where the second computer monitors the output of the Dynamic Beamformer and alters its operation based on what has been learned about the data.

In the selection of a particular hardware architecture for a digital time-domain beamformer, a number of interacting considerations come into play. The particular choices made

Dynamic Beamformer tape deck and terminal

Figure 9

On left is the vertical beam pattern of a thirty-two element array. On the right is the horizontal beam pattern of the same array.

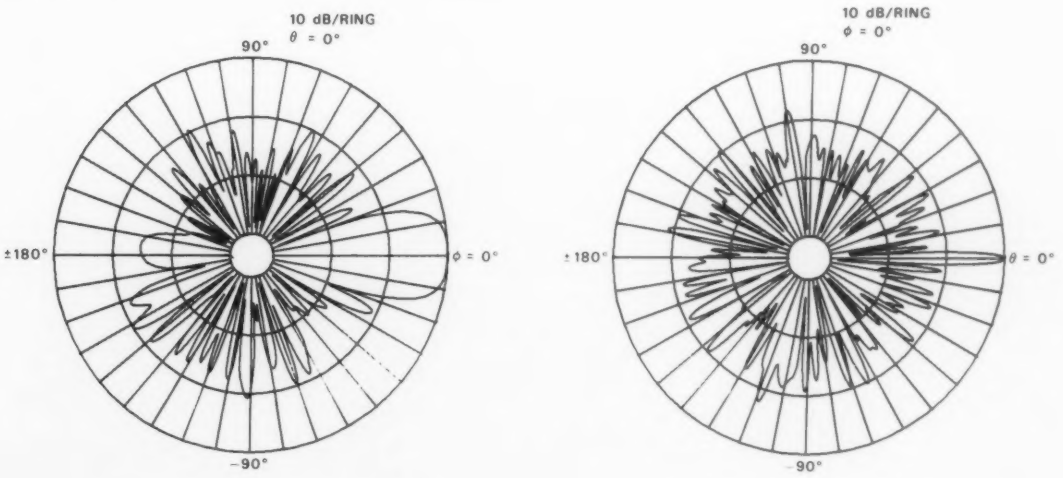
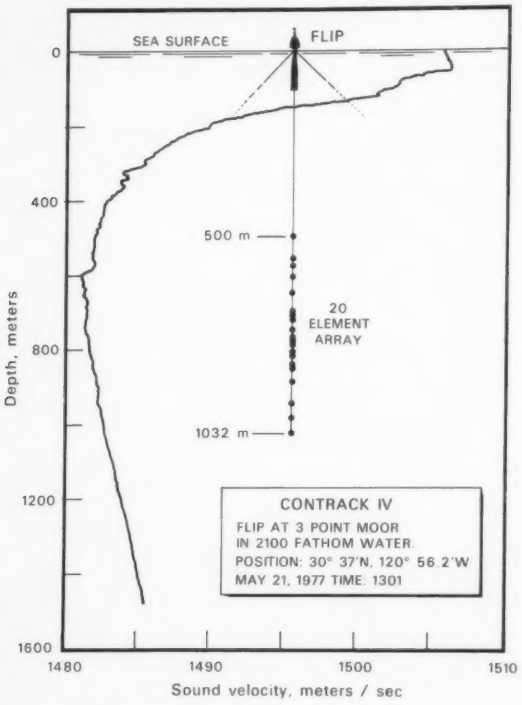


Figure 11

Schematic of FLIP in 3-point moor with the 20-element array deployed at sound channel axis, with sound velocity profile



for the MPL Dynamic Beamformer produced the following specifications: (1) bandwidth, 10–400 Hz, (2) number of channels, 32, (3) data sampling rate, 2 kHz, (4) interpolation (linear), 8 kHz, (5) maximum time delay, 2.048 s, (6) additional memory for block processing, 6.144 s, and (7) number of beams formed, 1300.

The hardware that has been fabricated permits the incorporation of slow changes in element positions and beam steering direction while the beamformer carries out the real-time formation of 1300 beams from 32 input sensors. The sensors are distributed in a random, but known manner over an aperture diameter of up to 3000 m. Their positions are determined by a separate array element location system that uses several active buoys within the predominant passive sonobuoy field.

Remote Underwater Manipulator (RUM)

For 90% of the world's oceans, the sea floor lies at depths between 500 m and 6000 m. Remotely operated towed survey systems such as Deep Tow have, for many years, been able to work at depths as great as 6000 meters and have been instrumental in extending our knowledge of deep seafloor phenomena. Comparable advances in understanding other seafloor processes await the capability of direct physical interaction with the sediment-water interface. This project at the Marine Physical Laboratory is developing a third of a succession of cable tethered and powered, tracked Remote Underwater Manipulators, RUM III, to provide such a seafloor work capability.[22]

The problem of decoupling the dynamics of a 6000 meter steel jacketed cable, hung from a surface ship in a seaway, from the vehicle in gentle contact with the very soft but fixed sediment/water interface of the seafloor, has been the greatest barrier to the development of deep ocean bottom-crawling vehicles. The problem is accentuated by the fact that the vehicle itself may have an in-water weight that is an order of magnitude less than that of the cable. Another obstacle has been the problem of positioning the vehicle over the desired spot for "set-down;" the response time for lateral motion of long umbilical cables is on the order of an hour, so that positioning by maneuvering the surface ship is very tedious at best. The poor stability of a vehicle in operating on the very soft sediments also poses a problem in accommodating overturn moments from cable drag or from dynamic manipulator loading. Turbidity from disturbed sediments is an impediment to optical viewing which also must be dealt with.

In spite of the development of sophisticated supervisory control systems and automation, none of the autonomous free swimming vehicles currently under development can be expected to have the unlimited endurance or mission time of the cable tethered RUM III which is so important for deep sea floor work or to have a communication link with a bandwidth adequate to support the adaptive manipulation requirements of intensive exploratory benthic investigations. Some of the

advantages of our cable tethered RUM III are: (1) that it does not require the life support or man-rated certification of a submersible, (2) it is cable-power rather than battery- energy limited and thus has virtually unlimited endurance, (3) the strain cable provides a predominantly fail-safe recovery system, (4) the wide bandwidth of a coaxial cable supports a far higher information rate than the next best alternative—an acoustic communication link, and (5) the ability to maintain physical contact with the bottom and to have controlled movement via the track system provides an essential capability for a seafloor work vehicle. In addition to these generic advantages, experience gained using RUM II demonstrated that the bottom crawling concept provides a powerful investigative tool for the intensive in situ study of benthic eco-systems at depths beyond diver access.[23]

An earlier design study by Dr. Victor C. Anderson's group for the seabed disposal project at Sandia has provided the basis for the vehicle now in development.

There will be several significant features which will be incorporated into the new RUM III design. The smooth large area track design of the Sandia study will be used for on-bottom positioning in soft sediments. Independently rotatable ballast weights will provide vehicle trim both when in the tow mode and when on the bottom. This will also alleviate the overturn problem on soft sediments when handling overside loads with the manipulator.

The cable attachment point will be coaxial with the manipulator turret mount so that a passive elastomer accumulator system can be employed which will provide constant tension of about 50 kg over a range of 15 meters. A cable stop will be incorporated for the overside launch and recovery process. In this way the existing Deep Tow shipboard handling system can be employed with minimum modification, obviating the need for a special shipboard handling system.

A boom mounted on the central rotating turret will be fitted with a lightweight manipulator. An underdetermined (3 degrees of freedom in the vertical plane) geometry will be used. The boom geometry will be constrained by the servo-control microprocessor. A pair of TV cameras on pan/tilt mounts will be mounted on the boom attached to the rotating turret. These can be oriented with respect to the manipulator for optimum viewing perspective or can be brought into close proximity of objects on the sea floor for magnified inspection.

Two lightweight controllable pitch thrusters mounted on the turret provide thrust efficiencies in excess of 50 kg/hp. They may be independently and dynamically feathered to generate a thrust vector in any horizontal direction and also provide rotational torque to the vehicle. The structure will be shrouded to reduce the hazards of entanglement, and a fin will be attached to the manipulator boom to stabilize the hull in the tow mode so that it can serve as a platform for side-looking sonar.

Cylindrical pressure-proof housings will be provided for both the basic system electronics and for custom electronics required for users. Electrical and mechanical interfaces will stress modularity to enhance the ability to install special instrumentation on the vehicle.

At the heart of the system is the telemetry and control electronics. The operating software follows the design developed for the MPL ADA array system.

The ocean medium is electrically conducting, corrosive, and exerts hydrostatic pressure up to 700 atmospheres. Needless to say, it creates a hostile environment for instruments and structures. A basic tenet of our design philosophy will be to minimize the hostile effects of the ocean medium and capitalize on some of its few advantages. Structural design will emphasize the use of plastic materials whose low density, offset by the buoyancy of the surrounding medium provides unusually high in-water strength-to-weight ratios. In-water weight will be a dominant constraint in order to permit operation on the low-strength deep sea sediments. Many standard electrical and electronic components can withstand the high hydrostatic pressure and operate well in an ambient pressure oil bath. This effect will be exploited in the design also. The nearly infinite heat sink of the ocean can be used to simplify the problem of cooling semiconductor controllers. Modularity in the design will be stressed to enhance adaptability of the vehicle for a variety of applications and to facilitate repair and maintenance. Standard components and proven techniques will be used whenever possible, however, there are a number of areas where innovative design will be required. With reasonable technical success and continuity of funding, RUM III should be ready for testing in 1984.

RUM III is a multi-agency funded project. Sea Grant, the Office of Naval Research, and private Fleishmann Funds at the Scripps Institution of Oceanography are underwriting the project.

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Profiles in Science

Eugen J. Skudrzyk is Professor Emeritus of Physics at The Pennsylvania State University where he has long held a joint appointment in the Department of Physics and the Applied Research Laboratory. A Fellow of the Acoustical Society of America, Dr. Skudrzyk has published and made research contributions in many areas of acoustics, including architectural and musical acoustics, flow noise, supersonic sound, ultrasonics, and vibration. Office of Naval Research (ONR) contract support and the collaboration of ONR staff contributed importantly to the preparation of Dr. Skudrzyk's books *Simple and Complex Vibratory Systems* (1968) and *The Foundations of Acoustics* (1971).

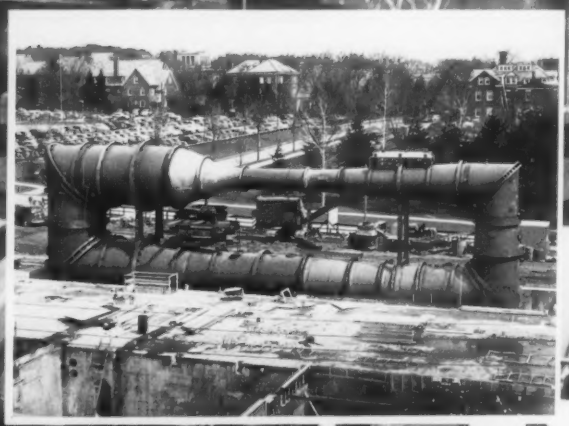
Dr. Skudrzyk came to Penn State and ARL in 1955 and received emeritus rank upon his retirement in 1978. With a long and productive career of research, publishing, teaching, and supervision of graduate students already to his credit, he continues to be active in all of these areas. He regularly contributes papers at meetings of the Acoustical Society of America and publishes papers in its *Journal*. Among his many noteworthy achievements are predicting acoustic diffraction produced by coated and uncoated steel plates and wedges, which is of considerable theoretical and practical significance for both the Navy and the research community at large, and on predicting vibratory response and acoustic radiation from intricate vibrating structures. In addition, he pursues as an avocation both theoretical and experimental research in the optics of photography.

Recognized internationally, Dr. Skudrzyk was the keynote speaker at the All-Soviet Acoustics Conference in Moscow in 1973. He received the Applied Research Laboratory's own Distinguished Performance Award in 1975 for research which led to a better understanding of hydromechanical generation, radiation, and transmission of acoustic energy. In July he received the prestigious "Rayleigh Medal for 1983" from the Council of the Institute of Acoustics of the United Kingdom in Edinburgh as well as the Silver Medal in Theoretical and Applied Acoustics presented by the Acoustical Society of America.

Hydrodynamics and Fluid Mechanics

by

Blaine R. Parkin
Applied Research Laboratory
The Pennsylvania State University



This 1949 photograph shows the just completed Garfield Thomas Water Tunnel with its 4-foot (1.22 m diameter) test section. The main Penn State campus is in the background. Turbulent boundary layer studies, supported by the Office of Naval Research, have been conducted in the water tunnel's test section since the early days.

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Introduction

It has been thirty-four years since the initiation of organized research in hydrodynamics and aerodynamics at the Garfield Thomas Water Tunnel (GTWT), Applied Research Laboratory (ARL), The Pennsylvania State University (PSU). Because of its need to enhance the hydrodynamic technology of acoustically guided torpedoes, the U.S. Navy Bureau of Ordnance built the 1.22 m water tunnel at the Ordnance Research Laboratory, The Pennsylvania State University, Figure 1. This 1.22 m cavitation tunnel is still a unique experimental facility for conducting hydrodynamic research in the United States although other cavitation tunnels possessing similar capabilities have since been put into operation abroad. Since its inception, the Garfield Thomas Water Tunnel has matured to become a versatile research laboratory in hydrodynamics and low-speed aerodynamics with a staff of about fifty scientific and technical people producing basic and applied research on ARL/PSU programs for the Navy and for the National Aeronautics and Space Administration (NASA), and in furtherance of the University's educational goals in engineering.

This work is carried out in the GTWT building which houses five water tunnels, a 1.22 m diameter low-turbulence wind tunnel, an axial-flow research fan, a cascade tunnel and a free-jet facility. A large flow-through anechoic chamber for turbomachinery aeroacoustic research is now partly built. These facilities, together with appropriate computer and data acquisition systems, enable the faculty to do research in cavitation, hydro/aeroacoustics, turbulence, transition, hydrodynamic drag, hydraulic and subsonic turbomachinery and marine propulsors. These facilities and their operating characteristics have been documented in various places.[1,2]

As might be expected, the capabilities of the GTWT to conduct hydrodynamic research have been extended significantly to meet increasingly complex requirements which have evolved over the years. Specific new capabilities of the 1.22 m water tunnel include noise measurements with and without cavitation; measurement of dynamic forces on model propulsors operating on a model vehicle; test section turbulence-level reduction to 0.1% with an integral scale of 1.25 cm;[3] and the development of electro-optical measuring techniques. These enhancements and accompanying improvements in other facilities have led to some expanded research thrust in recent years which are discussed in the following paragraphs.

Cavitation Research

Surface Roughness

Research in the mechanics of cavitation has been an important part of the work being done at the GTWT since its earliest days, and this work has continued to the present. A notable aspect of cavitation research at ARL has been that of surface roughness effects on cavitation onset. A comprehensive summary of results achieved on this particularly important problem up to 1979 has been given by Arndt et al.[4] This body of work concerns cavitation onset on distributed and isolated roughness on flat plates in the absence of pressure gradients. In the course of this work, it was found for isolated roughness elements that the turbulent boundary layer shape parameter, H, was helpful for correlating some of the data. Since we know that the value of the shape parameter depends on the streamwise pressure gradient, it seems reasonable to conjecture that the pressure gradient can influence cavitation onset on an isolated roughness element. An investigation of this possibility has just been completed in which the roughness element was placed on a flat plate and the pressure gradient was produced by shaping the opposite tunnel wall.[5] The effect of both favorable and unfavorable pressure gradients could be studied in this experiment and compared with results from reference 4. The results for a single two-dimensional triangular protrusion are shown in Figure 2. Here the kinematic viscosity of water is υ, and the symbol G denotes Clauser's integral family parameter for equilibrium turbulent velocity profiles. This correlation is thought to be very satisfactory. It was also found, compared to a zero pressure gradient flow, that a favorable pressure gradient has a lower cavitation number, and an adverse gradient has higher cavitation number for inception.

Scale Effects and Bubble Dynamics

Cavitation scale effects have also been under investigation for many years at many laboratories around the world. And it happens that cavitation inception on hemispherical headforms has probably received more extensive investigation than other shapes. Recently at the GTWT, Holl and Carroll[6] performed a series of experiments on a hemispherical nose in which detailed pressure distributions were obtained in the region of the minimum pressure and on into the short laminar separation bubble for a range of Reynolds numbers. They then continued on to produce inception data for a number of different forms of cavitation, one of them being bubble-ring cavitation. This form of inception is seen as a ring of very small bubbles in the flow region where the laminar bubble becomes turbulent, and the flow reattaches to the body. The Holl-Carroll data, when combined with earlier results from the California Institute of Technology (CIT) and the Netherlands Ship Model Basin at Wageningen, give a good picture of the flow in the boundary layer including the height and length of the laminar separation bubble. With these data in hand, it seemed to us that it was time to attempt a theoretical analysis, proceeding from the first principles of

Figure 2

An improved correlation for cavitation inception on an isolated two-dimensional triangular roughness with pressure gradients.

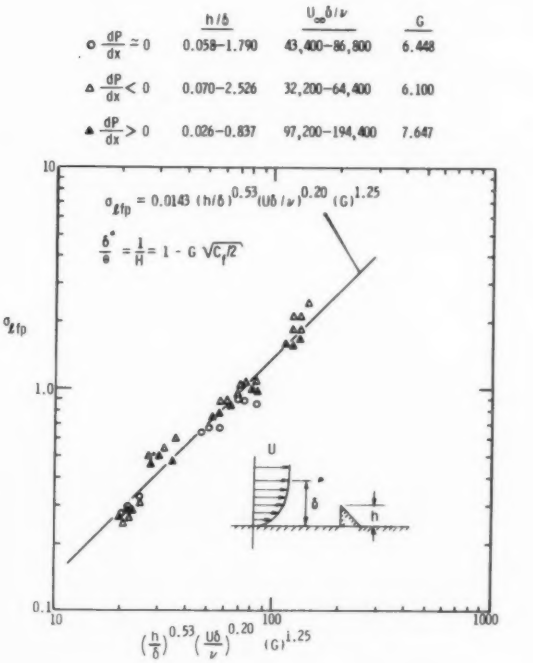
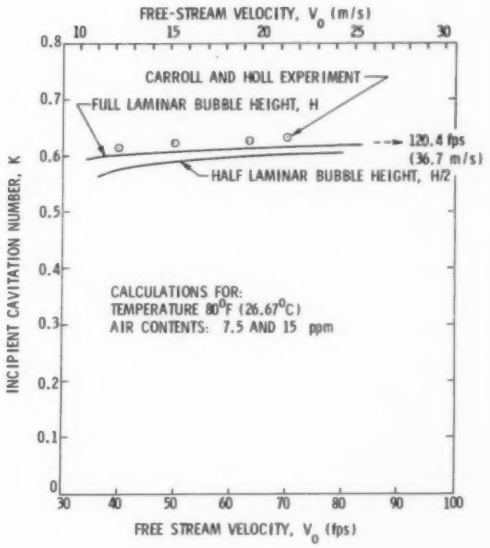


Figure 3

Comparison of experiment and theory for bubble-ring cavitation onset; calculated values of K for maximum vapor bubble radii on one-half laminar bubble height and equal to laminar bubble height are shown.



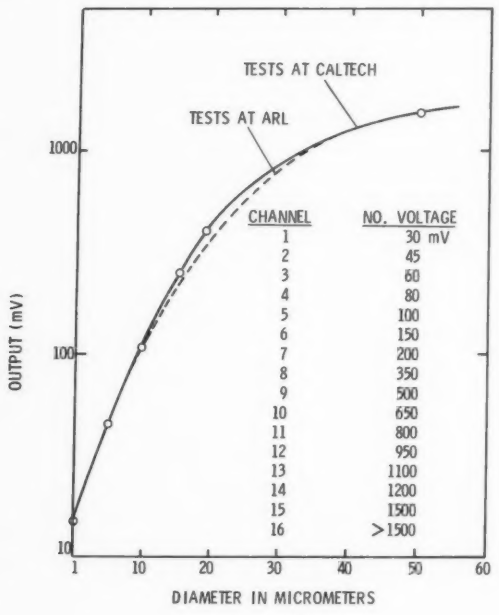
bubble dynamics, from which one might infer the important physical events which lead to bubble-ring cavitation inception. This work was carried out and the results of a new asymptotic theory are compared with experiment in Figure 3.[7] The agreement between experiment and theory is thought to be quite encouraging in view of the fact that previous attempts to use bubble dynamics for calculations of inception in any flow have never given more than rough qualitative agreement with experiment. Two encouraging features of the present theory, in agreement with experiment, are that bubble ring inception is independent of dissolved air content, provided there is some dissolved air in the water, and that there is a cavitation-cutoff speed which defines a free-stream velocity below which bubble-ring cavitation is not observed although other forms may be present. The cavitation-cutoff phenomenon was found by Holl and Carroll and discovered independently by experimenters in Japan at about the same time.

Free-Stream Nuclei and Inception

In recent years it has become recognized that cavitation inception and the forms of cavitation observed in the laboratory are sensitive to the distribution of cavitation nuclei in the water during a test. In fact, cavitation test results on standard bodies have been found to show wide variations between laboratories, and these differences nowadays are ascribed to differences in the free-stream microbubble populations in various facilities. It is presently thought that such microbubbles may have diameters as small as 10 or 15 microns, and that these are more numerous than the larger nuclei. The problem is to characterize accurately the nuclei population in any facility. Cavitation research workers have not been completely successful in this task thus far, although at the GTWT we believe a successful technique for routine laboratory use may be within our grasp. At ARL/PSU, both light-scattering

Figure 4

Calibration of light scattering nuclei counter at CIT and ARL/PSU.



and holographic techniques have been used for the measurement of free-stream nuclei size distributions. For example, it was found in a joint research program with CIT[8] that light scattering and holographic measurements produced significantly different nuclei size distributions when measurements were made by both methods in the same facility. Such dual measurements were made at CIT in their high speed and low turbulence tunnels,[9,10] and suplementary light-scattering measurements were made in the ARL/PSU 0.305 m tunnel. In these experiments the light-scattering unit was of a type similar to that proposed by Keller.[11] The results obtained at CIT and ARL/PSU are shown in the calibration curves in Figure 4. Comparative nuclei distributions measured by the light scattering and holographic techniques in the CIT high speed water tunnel are shown in Figure 5. It was concluded from these experiments that the light scattering technique was not able to discriminate between solid particles and air microbubbles in the flow.

As a result of these findings, recent studies at ARL/PSU have concentrated on the development of a dual-detector technique which, with the use of Mie-scattering theory, can give information about the shape of the particle. This permits the light scattering technique to discriminate between microbubbles and particulates, Figure 6. The results to date indicate that this modified Keller system offers the potential of screening particulates from the microbubble counts.[12] The main task remaining before this approach can be called successful is to conduct a detailed error analysis in order to resolve the system inaccuracy introduced by the data reduction algorithm. Because the light scattering technique offers the chance of getting nearly real-time nuclei distribution data while a cavitation test is in progress, this improvement of the Keller system is worth pursuing.

Assuming that valid nuclei size distributions can be obtained while a cavitation experiment is underway, the question of how such distributions influence the development of cavitation on a body must be studied. Such a study can be conducted if the cavitation events can be related to such flow features as the boundary layer thickness or whether or not the flow is separated. Schlieren flow visualization is an effective way to show the relationship of cavitation inception and its type to the state of the boundary layer.[13] Measurements of this type have been performed in the ARL/PSU 0.305 m tunnel using light scattering and Schlieren systems simultaneously as illustrated in Figure 7,[14] but much more remains to be done to complete the investigation.

Of course holographic photography can be used for flow visualization with excellent results in both cavitating and non-cavitating flows, but we have not developed a real-time analysis capability for this technique at the GTWT.

Cavitation Damage

The 3.81 cm NASA tunnel at ARL/PSU and its very high velocity, up to 83.8 m/s, has been used to study the process of cavitation damage.[15,16] Recent studies at ARL/PSU have confirmed the sixth-power variation of the free-

Figure 5

A comparison of nuclei distributions measured in light scattering and holographic systems.

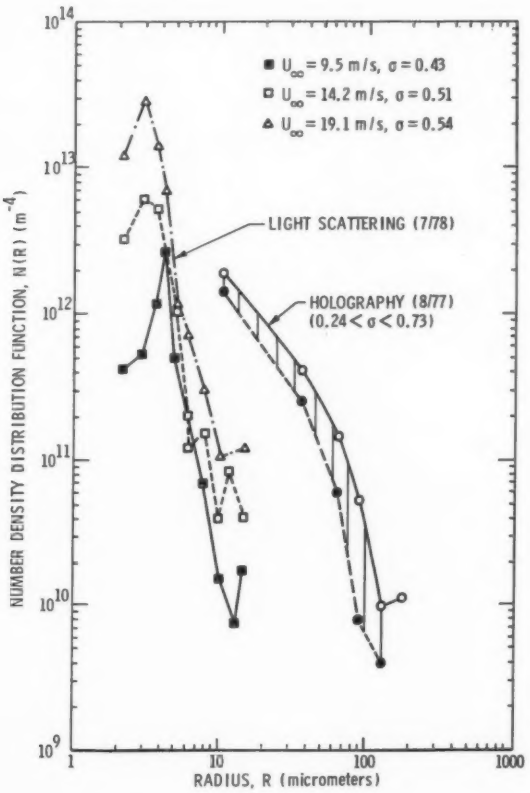


Figure 6

Schematic of the dual-detector light scattering system.

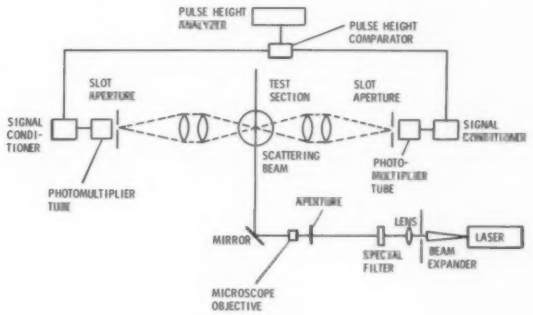
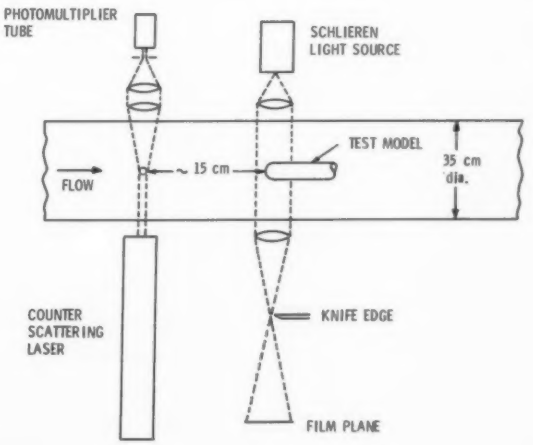


Figure 7

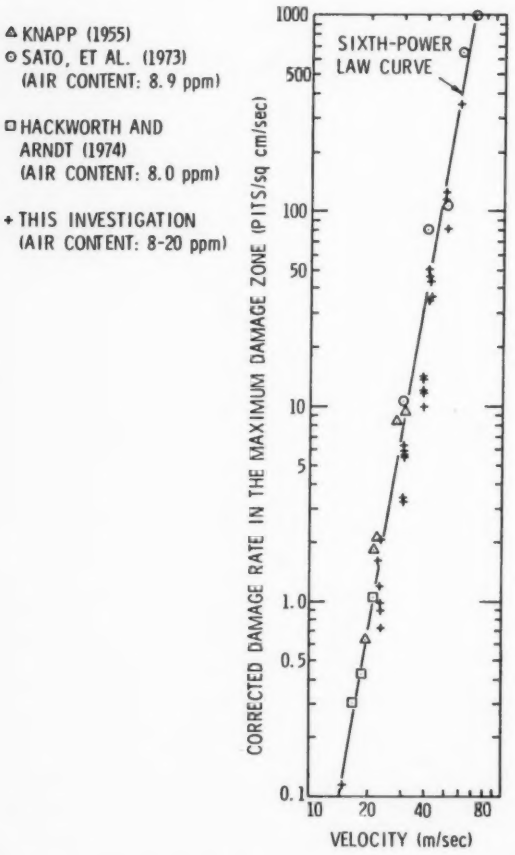
Schematic of the Schlierew flow visualization and laser light scattering systems.



stream velocity scaling relation reported by previous investigators. In the GTWT studies, it was possible to obtain nearly a four-fold change in velocity, from about 15 m/s to 60 m/s. A fact not previously reported is that the pitting rate in the incubation zone is sensitive to, and inversely proportional to, the dissolved air content. Therefore, it was possible to correct all of the data to a standard air content of 8.9 ppm so that data for all investigations over a 10,000 to 1 range in damage rates could be brought into remarkable agreement, Figure 8. It is important to stress that this investigation involved the study of pitting on a body without the occurrence of weight loss. With this restriction, it was found that damage in the form of individual pits had a one-to-one

Figure 8

Damage rate vs velocity from various investigations.



correspondence with the cavitation bubble collapse energy, and the change in this energy with free-stream velocity could be inferred from this observation.

Drag and Drag-Reduction Research

Tunnel Wall Effects and Drag Measurements

Vehicle program managers have always needed accurate drag data early in a program. In the case of submerged vehicles where wave drag is not a factor, a large water tunnel such as the 1.22 m tunnel at the GTWT can provide a basis for accurate drag estimates. An advantage offered by the tunnel is that interferences due to water waves and surface-piercing struts are not present. Moreover, it is possible to run the model, and in particular, the propulsor, at higher Reynolds numbers which simplifies the task of scaling propulsor powering data. However, the need to produce accurate propulsor powering estimates has led to the use of rather large models at the GTWT so that traditional wind-tunnel test methods which are useful in cases where the tunnel wall effects are not too large can not be used without modificaton in the 1.22 m water tunnel.

Among the earliest of our attempts to investigate the wall effects problem, at least for propulsor powering tests, has been the use of tunnel-wall flow-correcting liners.[17] Except for fluid frictional effects, these liners are designed to give the same flow over the model as it would experience if the walls were not present. Nowadays, this tunnel wall shaping is done by calculating the flow around the model with and without walls being present, allowing for boundary layer growth. It has been found that such tunnel-wall liners will provide the same boundary layer velocity profile at a propulsor inlet as measured in a towing tank or in a very large wind tunnel where tunnel wall interference is negligible.

An additional complication is introduced in water tunnel testing if at model scale the prototype configuration requires the water tunnel model to be longer than the 4.5 m length of the 1.22 m diameter test section. Then part of the model's parallel mid-section must be removed. We compensate for the effect of this removed section on the propulsor inflow velocity profile by the addition of boundary-layer-thickening screens which add the same incremental skin friction as would be produced by the missing body section.

Experience has shown that while flow liners and screens can provide the correct velocity distribution on the body, they can not be fabricated and installed so as to eliminate horizontal buoyancy and its effect on vehicle drag.[18] However, during the past ten years, further research on this entire matter has shown that empirically based correction procedures can be developed to take care of the above sources of error.[1] Figure 9 gives an example of the results obtained from this correction procedure applied to water tunnel data and compared to trial

data from a freely swimming vehicle. Both speed and propeller torque of the vehicle are compared in this graph. The curves of Figure 9 were produced before the vehicle field trials were run.

The reasons for ARL's continuing research in drag and powering measurement is clear. The "other side of the coin" is research directed at possible methods of drag reduction. Past research at ARL/PSU have studied boundary layer control by the use of suction slots and drag reduction by means of dilute polymer solutions. Most recently, our research in drag reduction has centered on heated laminar boundary layer stabilization and on the influence of microbubble injection upon turbulent drag reduction. Both of these experimental programs are currently underway and some preliminary findings can be presented.

Heated-Wall Laminar Boundary Layer Stabilization

The 3.21 m long water tunnel model of the ARL/PSU heated body is shown schematically in Figure 10 which illustrates the method of heating employed. Prior to the installation of the heated body in the 1.22 m water tunnel, an unheated body of the same shape and size was run in the tunnel in order to measure the pressure distribution and cold-body transition characteristics as they pertain to the heated body experiments.[19,20] These investigations provided procedures which allow the effects of blockage and wall and body skin friction to be used in a correction procedure which is applied to calculations for the potential flow pressure distribution about a body of revolution in the tunnel at Reynolds numbers of the experiments. These results then gave a basis for transition predictions and measurements in the arc-length Reynolds number range of 9.55-47.7 million on the unheated body because the pressure distributions can be tied to the Reynolds numbers of the tests. Theoretical calculations of the transition Reynolds numbers for this body shape, which allowed for free-stream turbulence, were correlated with the experimental data. It was found that good correlation can be achieved if e^n is chosen as the transition criterion in the linear stability calculations. Here n is an empirical number depending on the turbulence intensity. It was found that this number approached 9 for those test velocities where the free-stream turbulence intensity was of the order of 0.1%.[20]

These cold body data demonstrated that research on boundary layer stabilization can be carried out in the 1.22 m tunnel. When the experiments with the heated body were initiated in FY 1982, it was found that premature transition is related to the presence of dissolved air in the water. The higher the dissolved air content, the sooner transition was found to occur. It is known that dissolved air promotes the existence of microbubbles in the water. Many of these will have diameters under ten microns as illustrated in Figure 5. Such small bubbles will behave very much like solid particulates when they enter the laminar boundary layer where their presence can cause early transition if their concentration is high enough. It can be conjectured that the concentration of microbubbles is proportional to the dissolved air content as

Figure 9

Comparison of water tunnel and field-trial propulsion data.

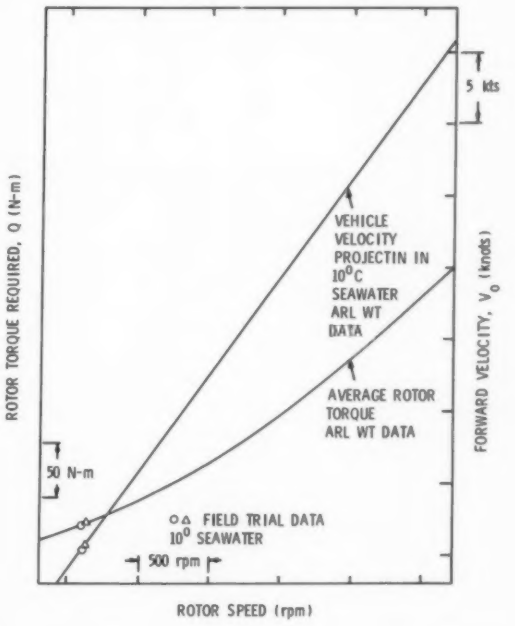

ROTOR TORQUE REQUIRED, Q (N-m)
FORWARD VELOCITY, V_0 (knots)
5 kts
VEHICLE VELOCITY PROJECTIN IN 10^0C SEAWATER ARL WT DATA
AVERAGE ROTOR TORQUE ARL WT DATA
50 N-m
FIELD TRIAL DATA 10^0 SEAWATER
500 rpm
ROTOR SPEED (rpm)

Figure 10

The GTWT heated body for research on laminar boundary layer stabilization.

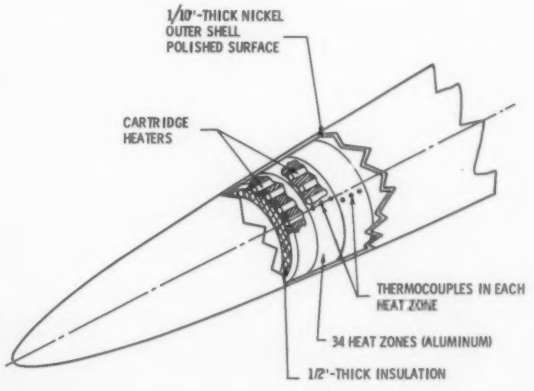


Figure 11

Effect of microbubble particulates on heated boundary layer transition from laminar to turbulent flow.

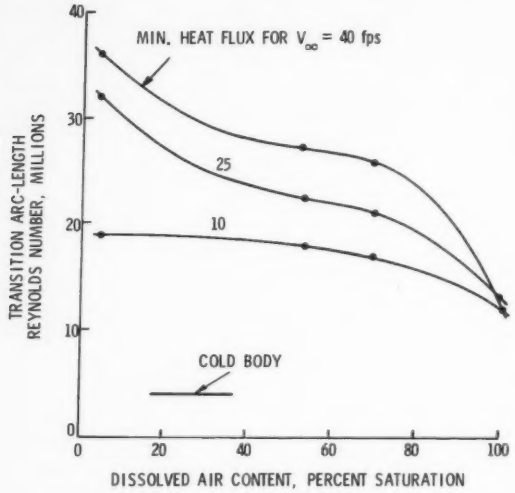
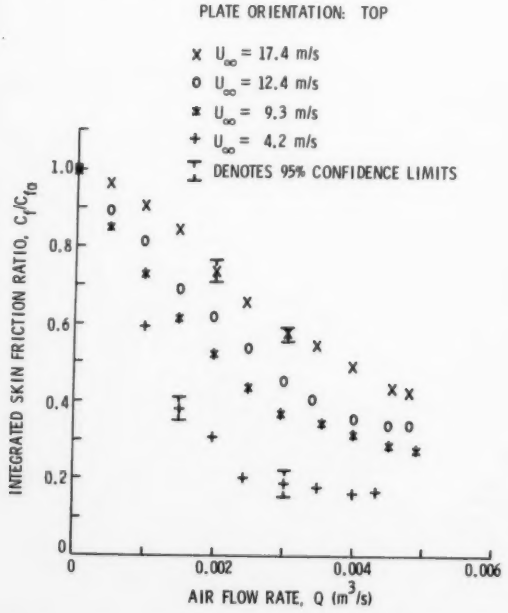


Figure 12

Ratio of integrated skin friction in the presence of microbubbles to skin friction without microbubbles as a function of air flow rate. Plate above the boundary layer.



measured by a van Slyke apparatus so that this parameter is a measure of the microbubble concentration. This does not rule out possible destabilization caused by small-sized solid particulates too.

As a result of these initial observations, it was deemed important to investigate this aspect of heated boundary stabilization more systematically. The results of this investigation are shown in Figure 11. Three heating rates were selected for a range of dissolved air content, and the resulting transition Reynolds numbers as detected by a hot-film probe were compared with the unheated-body transition data. Figure 11 shows that the application of heat will delay transition at all air contents investigated. However, these data show that as the air content and presumably, the number and size of free microbubbles in the water increases, the beneficial effect of heating is limited. However, the question of solid particulates in the water remains. A recent GTWT holographic study showed, in the experiments just described, that the number density of microbubbles in the water changed by a factor of about two, but that the solid microparticulate concentration changed by more than an order of magnitude and that the mixture of air and solid particulates was predominately solid. The reason for the observed trends is that the bypass leading from the water tunnel to the air separator contains a filter so that the system reduces microbubble and solid particulates simultaneously. These results suggest for vehicles operating in the mixed layer of the oceans (and perhaps at greater depths) that methods of boundary-layer particulate control warrant serious study.

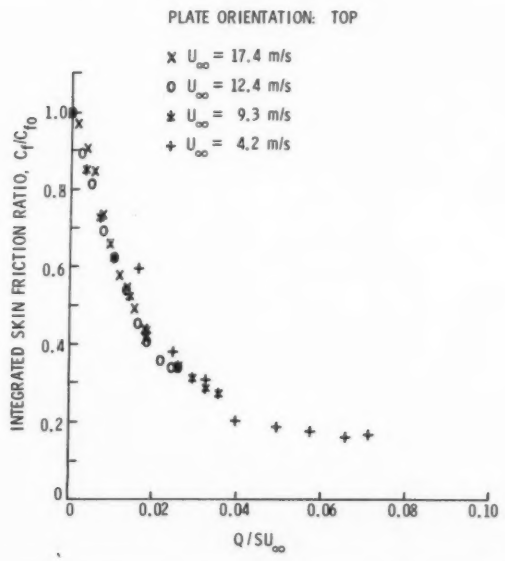
Microbubble Injection and Drag Reduction

As noted already the other current effort in drag-reduction research is that of microbubble injection into the boundary layer. This work is the result of an ONR program initiated jointly by the Mechanical Engineering Department and the Applied Research Laboratory at Penn State. In this work, the effects of a high concentration of very small bubbles on the skin friction characteristics of a turbulent boundary layer are being investigated experimentally. The microbubbles are generated by injecting air through a porous section of the wall. The objectives of the research are to document the ranges of air flow, water velocity and bubble size for which the bubbles are effective. Initial efforts were concentrated on determining the integrated skin friction on a 25.4 cm metric section immediately downstream of the porous material. Current efforts are directed toward measuring the local skin friction.

Results of the integrated skin friction measurements are shown in Figures 12–13. Figure 12 shows measurements with the boundary layer below the plate so that gravity tends to keep the bubbles in the boundary layer. As can be seen, skin friction reductions of as much as 80 percent can be realized.

Figure 13

Dimensionless skin friction as a function of dimensionless injection rate. Plate above the boundary layer.



The same data are presented in Figure 13 in a normalized form which collapses the data into a single band. Figure 14 presents the reductions which were observed when the boundary layer was above the plate (so that the effect of gravity is to remove the bubbles from the boundary layer). These results indicate that less skin friction reduction can be realized in this configuration, particularly at the lower speeds.

Local skin friction measurements are in qualitative agreement with the integrated measurements and with previous Soviet results. Measurements with a single probe located 5.08 cm downstream of the porous section are shown in Figure 15. These show local reductions of nearly 90 percent. Measurements with multiple local skin friction probes are currently in progress. These measurements should give an indication of the variation in local skin friction with distance downstream of the porous section.

In addition to the skin friction measurements, the characteristics of the boundary layer into which the bubbles are injected have been measured to document the undisturbed boundary layer; and some limited velocity profile measurements in the presence of microbubbles with low bubble flow rates have also been obtained. Finally, the effect of changing the size of the porous section and changing the pore size have also been documented.

Figure 14

Effects of buoyancy on skin friction reduction. Comparison of data taken with plate on top and plate on bottom.

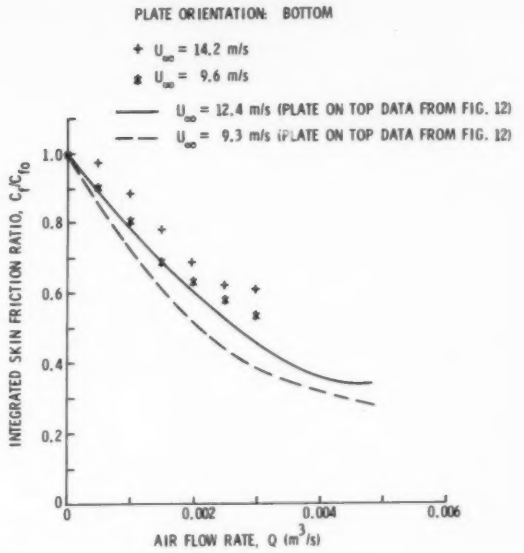


Figure 15

Local skin friction as measured with surface-mounted hot film. Plate on bottom of tunnel.

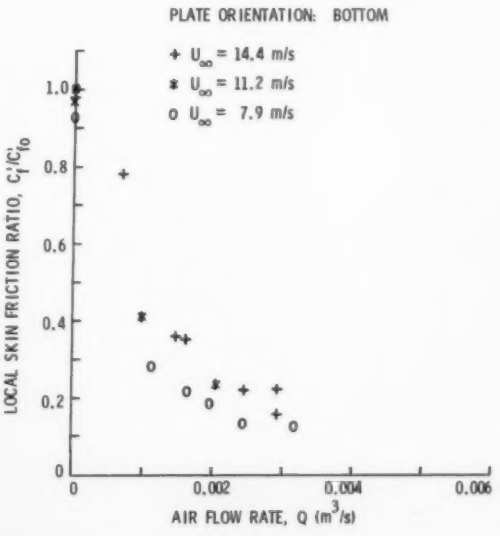


Figure 16

Downstream array in the 48-inch water tunnel.

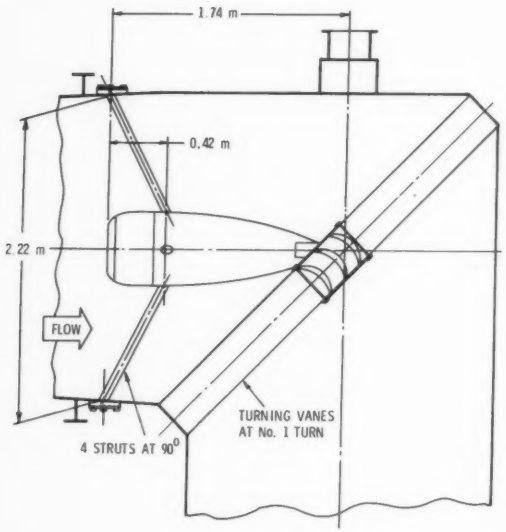
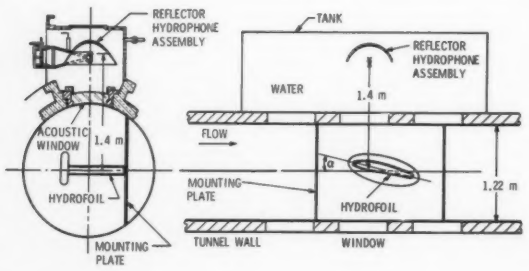


Figure 17

Acoustic tank and reflector hydrophone arrangement.



Hydrodynamic Noise

One reason for studying the basic hydrodynamics of unsteady flows and spatially irregular steady flows is because these flows can create propulsor noise or excite vibrations of the contiguous structure which can lead to acoustic radiation. In addition, flow noise associated with the turbulent boundary layer on a body can lead to unwanted acoustic signals. Finally, cavitation is a notorious noise producer. In spite of the apparent need for better acoustic data and the fact that the 1.22 m tunnel was designed for quiet vibration-free operation over a significant range of flow speeds, this facility was not used for detailed acoustic measurements during its first twenty years of operations.

Instrumentation and Facilities

Our ability to make the various kinds of noise measurements noted above has been enhanced in recent years by a number of advances in instrumentation so that now measurements are possible to make which were not contemplated in the past.[1] Of course, the 1.22 m tunnel has always had a side-mounted acoustic tank and traversing reflector hydrophone which can be focused on the centerline of the test section. Recently, a special acoustically transparent hatch has been built to fit in the space normally occupied by the original bronze test-section access cover. This new hatch has a large plexiglass window .4 m wide by 3.0 m long, and it is at the bottom of a large tank which can be filled with water so that additional hydrophones can be installed and traversed over most of the test section length. And finally, the water tunnel has also been outfitted with a downstream array of 69 parallel-wired hydrophones located at the diffuser turning vanes downstream from the test section. This sensor, shown in Figure 16, permits the far-field radiated noise to be measured at frequencies greater than 300 Hz. When used in conjunction with other sensors located in the test section, dual-channel signal processing can be used to identify propeller noise sources and propagation paths.

In addition to the acoustic instrumentation described above, a model motor and drive system which operates at the lowest possible mechanical noise level is used to conduct model propeller noise measurements. This permits measurements to be made at the highest possible signal-to-noise ratio, and it is accomplished with a specially designed motor/dynamometer. With this set-up, the background noise spectrum is measured with the tunnel flowing but with a rotating bare hub. Then the propeller noise measurements are made at the same flow speed and rpm.

Cavitation Noise

With these preliminaries out of the way, some specific results can be discussed. For example, cavitation noise is one topic of considerable research interest in a number of laboratories. Figure 17 shows a stationary hydrofoil installed in the 1.22 m water tunnel test section in order to determine the

effects of Reynolds number on cavitation noise. Four geometrically similar foils of different sizes were tested. The variation with scale of leading-edge sheet cavitation noise radiation was determined for cavity lengths ⅓ of the hydrofoil chord. In separate flow visualization tests, the 3.81 and 7.62 cm hydrofoils were shown to experience long and short laminer separation bubbles, respectively. On the other hand, the 15.24 and 30.48 cm hydrofoils exhibited attached turbulent boundary layer flow. A complete account of these results is given elsewhere,[21] but these tests did show the effect of laminar boundry layer separation and the noise produced.

Flow-Noise Theory

Of course, analytical investigations of flow noise in noncavitating flows are certainly of interest to workers in this field. In a recent study of boundary-layer flow noise caused by laminar-to-turbulent transition, Lauchle worked out the consequences when the acoustic radiation is ascribed to fluctuations of displacement thickness of turbulent bursts during transition.[22] He compared his results with measurements of De Metz and Casarella[23] for transition on a flat plate and with Haddle and Skudrzyk,[24] who measured flow noise on a buoyant body in water. The results of the comparison with Haddle and Skudrzyk are shown in Figure 18 for noise measured on the body surface and in Figure 19 for far-field noise measurements. Figure 19 also shows a comparison of the noise contribution of fluctuating shear stresses during transition.[25] It is seen that flow noise production from this source is weak compared to the sound generated by a fully developed turbulent boundary layer. It is worth mentioning that the rise time associated with turbulent bursts is a crucial parameter in a Lauchle's theory which he evaluated by a dimensional analysis. The theoretical model was not "tuned" by fitting it to any experimental noise data even though the theory contains a number of heuristic assumptions which require further research for justification.

Flow Field Measurements

An important part of hydrodynamic research has always depended on measurements of flow field velocities and pressures associated with various test configurations. Consequently, the development of pressure, hot-film, and hot wire probes as well as other instrumentation has been a continuing activity at most fluid mechanics laboratories. With the development of the laser Doppler velocimeter (LDV), it has been necessary to master its use for routine flow measurements and to develop new methods for using it in special situations. One special application of the LDV which has been developed at ARL/PSU is the development of a data acquisition system which permits measurement of the flow field relative to a rotating propeller. A schematic of this system is shown in Figure 20. The data control system,

Figure 18

Comparison of the theory with an experimental spectrum measured on the surface of a buoyantly-propelled vehicle by Haddle and Skudrzyk.

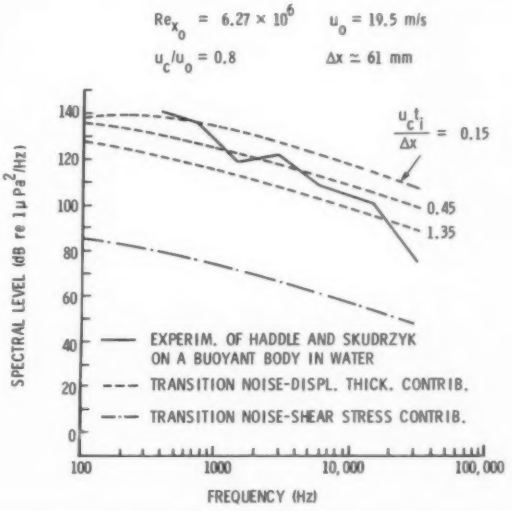

$Re_{x_0} = 6.27 \times 10^6$
$u_0 = 19.5$ m/s
$u_c/u_0 = 0.8$
$\Delta x \simeq 61$ mm
$\frac{u_c t_i}{\Delta x} = 0.15$
0.45
1.35
EXPERIM. OF HADDLE AND SKUDRZYK ON A BUOYANT BODY IN WATER
TRANSITION NOISE-DISPL. THICK. CONTRIB.
TRANSITION NOISE-SHEAR STRESS CONTRIB.
SPECTRAL LEVEL (dB re 1 μ Pa²/Hz)
FREQUENCY (Hz)

Figure 19

Comparison of the theory with an experimental spectrum measured far away from the rising buoyant body of Haddle and Skudrzyk.

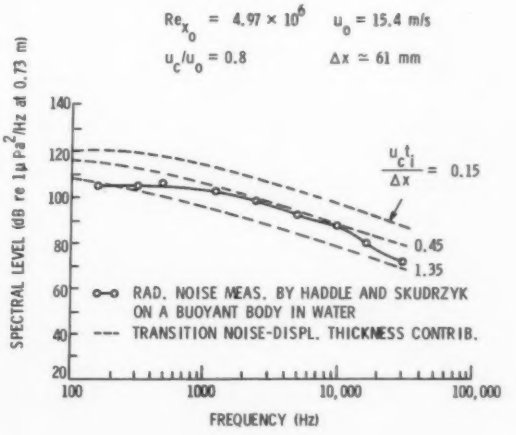
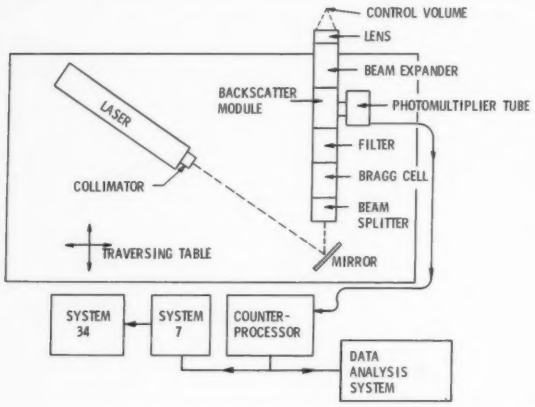

$Re_{x_0} = 4.97 \times 10^6$
$u_0 = 15.4$ m/s
$u_c/u_0 = 0.8$
$\Delta x \simeq 61$ mm
$\frac{u_c t_i}{\Delta x} = 0.15$
0.45
1.35
RAD. NOISE MEAS. BY HADDLE AND SKUDRZYK ON A BUOYANT BODY IN WATER
TRANSITION NOISE-DISPL. THICKNESS CONTRIB.
SPECTRAL LEVEL (dB re 1 μ Pa²/Hz at 0.73 m)
FREQUENCY (Hz)

Figure 20

Laser Doppler velocimeter for measuring velocities relative to a rotating propeller.



which was designed and built at ARL/PSU, is the heart of this system. An encoder, attached to the propeller shaft, provides the system with a signal which enables the control system to choose the instant that the laser beam is focused at a selected position with respect to the rotating propeller. The scattered light signal is accepted by the photomultiplier at that instant for processing, and the control system passes on to the next preselected point. In this manner, the velocity field relative to the propeller can be constructed point by point. indeed, using this method, ARL/PSU faculty have been able to measure the flow between the blades of rotating propellers as well as the relative flow ahead of and in the propulsor wake.

Of course, the LDV can also be employed to measure the flow field relative to a coordinate system fixed with respect to the laboratory; and because the LDV is non-intrusive, it is particularly useful for measurements involving vortex flows. Often the insertion of a conventional probe in a vortex core will lead to premature vortex bursting. Examples of axial and tangential velocities measured about one blade chord length behind a propeller are shown in Figures 21 and 22.[26] The use of the propeller shaft encoder with this setup enables one to determine the angular position of the blades with respect to the laser control volume so that the individual flows behind each blade can be measured. Thus, one can detect those blades which produce comparatively large axial wake defects or which produce higher or lower swirl velocities compared to other blades in the propeller and are related to some blade-to-blade fabrication variability. When radial and tangential velocity components are combined at each radial and azimuthal station and at a prescribed distance behind the propeller, a vector map of the vortex flows produced by the blades can also be created.

Concluding Remarks

This paper has presented some of the progress at the GTWT in hydro- and aerodynamic research within roughly the past ten years. This progress is the result of improved instrumentation and related experimental techniques. In summary, these advances have involved the development of better corrections for tunnel wall interference on powered model drag measurements; electro-optic techniques for measuring velocity fields and cavitation nuclei; techniques to study cavitation damage in high velocity flows; the enhanced capability to measure cavitating and non-cavitating propeller noise; and the development of better dynamometers to measure propeller and other dynamic forces. It is earnestly hoped that similar progress in terms of techniques and research output can be recorded in the next ten years.

Figure 21

Axial velocity V_x vs angle for x = 2.659 inches, R/R_p = 0.805 (No. 254).

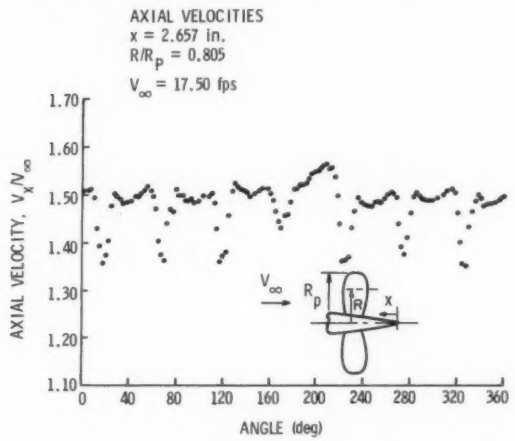
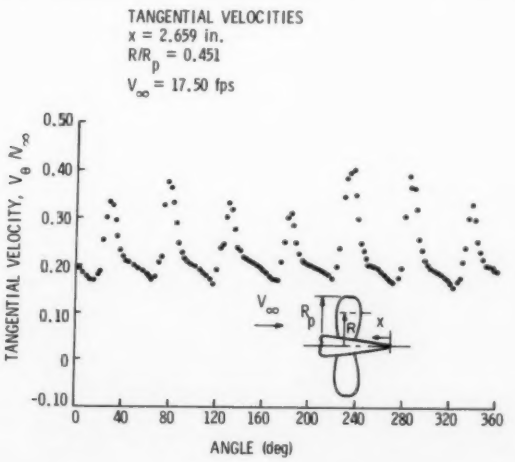


Figure 22

Tangential Velocity V_θ vs angle for x = 2.659 inches, R/R_p = 0.451 (No. 231).



Acknowledgment

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Shallow Water Acoustics

by

T. G. Muir
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The University of Texas at Austin

Introduction

Suppose you have been given the task of outfitting an expedition to locate the wreck of John Paul Jones' flagship, the BONHOMME RICHARD, which sank in shallow water off the Yorkshire coast after the most famous naval battle of the Revolutionary War. You've got a good budget, so you fit out your search vessel with the finest commercial gear money can buy. The most important of these will be the electromagnetic and acoustic systems, with which you will navigate, communicate, and execute your search mission.

After months of preparation in an east coast port, you sail for England on a great circle route. In the shallow seas of the Georges Banks, you decide to test out your acoustic systems.

You switch on a large, low-frequency sonar that sends out tone bursts and receives echoes from targets like shipwrecks buried in the bottom. The test results are disturbing because the sonar echoes sound like a coyote howling in a reverberant cathedral and not at all like those nifty sound tracks in the submarine movies of World War II vintage.

You put your divers in the water to test out an underwater acoustic communications system. Another disappointment, the words come out of the headset sounding like Donald Duck talking to his nephews, and you have to strain to unravel the conversation.

Finally, you deploy a transponder beacon, which is supposed to sit on the bottom and send out "beeps" to mark interesting targets for subsequent reacquisition and further study. Although you can recognize some beeps, most of what comes out of your passive receiver is noise radiated by the machinery on your own vessel. Self-noise in shallow water is especially troublesome since it bounces back and forth between the ocean surface and bottom and, consequently, remains quite intense in the working area.

Later in the voyage, as you approach the British Isles over the deep waters of the Biscay Abyssal Plain, these systems are tested again, this time with excellent results. In the much deeper water, there is considerably less reverberation and less noise. Although your systems work well in deep water, there is some concern because you are approaching the Celtic Shelf and then going over it to a truly shallow water site in the North Sea, where the survey expedition will take place.

Your expedition (like the one upon which this narrative is based) will be a dismal failure, due in large part to the harsh peculiarities of the acoustic situation in shallow water. Although marine archaeologists have located many fascinating shipwrecks, mostly those lying on the bottom in fairly calm water, this becomes more difficult in the North Sea, where storms and ocean currents tend to scour sunken artifacts into the bottom, further demolishing them and hiding them in the shifting sands.

Many acoustic systems have difficulty with the shallow water environment. After all, it occupies only 15% of the areal extent of the oceans and presents a special interest case when it comes to applications of underwater sound, including many more applications than those mentioned here.

Although it may be of limited or special interest, a broad spectrum of scientists and sailors have long been concerned with shallow water research and development. To the naval officer and scientist, shallow water is important, simply because naval actions have a way of cropping up there. In World War II, 39% of all ships sunk were sunk in shallow water. Then, there were the shallow seas around Korea, Vietnam, and, most recently, the Falkland Islands. The North Sea is very shallow (typically 50 m), as is the Baltic. Portions of the Mediterranean are shallow, as are the various gulfs and seas surrounding the Mideast countries.

Sound Propagation

In order to deal with shallow water, we have to know something about it and this means research in key areas of physics, geophysics, oceanography, and engineering. A considerable amount of research has already been done on how sound propagates in the ocean (Figure 1, taken from Reference 1).

Perhaps the most important difference between sound propagation in deep and shallow seas is the involvement with the surface and bottom. Sound rays transmitted in the deep ocean can travel relatively great distances between boundary reflections.

In shallow water, one encounters the boundaries almost immediately. Sound rays appear to ricochet between surface and bottom as they propagate. The process is actually more complicated (Figure 2) and involves several physical principles.

The first is the critical angle principle. Rays encountering the bottom at angles greater than the critical grazing angle for the prevalent sediment simply propagate into the earth and are lost forever. Less steep rays are internally reflected within the water column, with a small but finite loss of intensity at each bounce. Due to phase shifts at the boundaries and differing propagation paths, these rays tend to interfere in a chaotic fashion.

The medium itself tries to make some sense out of this chaos, and we appeal to the principle of the waveguide to explain the situation. Here the medium selects those rays and ray bundles where angular reflections reinforce, and groups them into modes. A mode is a series of upgoing and downgoing plane waves whose propagation vectors make small, but characteristic, angles with the horizontal. Since these angles become steeper with increase in modal number, higher order modes take longer to travel down the horizontal waveguide than do lower order modes. This gives rise to a geometric dispersion that causes acoustic pulses to be elongated. Eventually, at great ranges, the modes run away from each other creating a series of separate, well behaved signals. Unfortunately, at ranges of practical interest, the modes usually overlap one another, and interfere with one another, giving us garbled signals with numerous hot spots and dead spots (zones of constructive and destructive interference). All of these things can happen in an idealized isothermal ocean. When the sun heats up the ocean's surface, sound rays and modes are refracted downward, causing even more interaction and involvement with the bottom.

Shallow Water Experiments

Although a respectable body of theory has evolved in shallow water acoustics, we here use experiments to illustrate the evolution of science and technology. To date, the vast majority of shallow water measurements have focused on propagation effects. Most of these measurements have been done with explosive shots (Figure 3, taken from Reference 2). The shot (say 180 g of TNT) is armed and thrown in the water from a small boat; it begins to sink and explodes at a predetermined depth. A vertical hydrophone array receives the propagating acoustic signals downrange. They are recorded on magnetic tape and computer analyzed, typically in terms of energy content partitioned in 1/3 octave frequency bands.

Historically, the explosive shot has been extremely useful in delineating propagation losses as a function of frequency, over a given path. When plotted in terms of contours (frequency vs range, Figure 3), we can determine the optimum frequency for minimal propagation loss.[2] The optimum frequency usually occurs in the 25–1000 Hz band (depending on the water depth) as a result of competing loss mechanisms. At high frequencies, we experience scattering losses, caused by the roughness of the surface and bottom, while at low frequencies we experience bottom losses due to the leakage of modal energy into the sediments (Figure 2). The greater the water depth, the lower the optimum frequency.

Although the explosive shot has been useful in determining propagation losses, it is inadequate for research on more arcane topics. Signal processing research, for example, demands the use of signals with large time-bandwidth products (pulselength x frequency content). The shot produces a transient signal with a time-bandwidth of only one, while a typical pseudo-random noise burst, such as may be used in a modern signal processing scheme, may have a time-bandwidth of one hundred.

New Research Tools

Several types of research tools are currently available, or could be developed with existing technology (Figure 4). In addition to the need for larger time-bandwidth products, shallow water imposes a demanding requirement for research tools with spatial directivity. Directivity is essential if we are to isolate and examine the competing geophysical mechanisms. It is not sufficient, for example, to say that the scattering was high in a particular experiment. We need to know *which* scattering mechanisms, i.e., bottom, surface, or volume (fishes), and we need to further quantify the scattering strengths.

One achieves directivity with arrays of acoustic elements. Air guns (discharge of compressed air through mechanical devices) and sparkers (discharge of electricity between electrodes) have been used in the offshore seismic industry and they can be combined in high intensity arrays offering some bandwidth and directivity. Electroacoustic arrays (electrically driven piezoceramics) are widely used in both naval research and operations. They will likely produce greater bandwidth and directivity, even though they are large

Figure 1

Sound rays in the ocean. Deep water paths include surface duct-A, deep sound channel-B, convergence zone-C, bottom bounce-D. Shallow water paths are characterized by waveguide propagation-E, with considerable involvement of the surface and bottom.

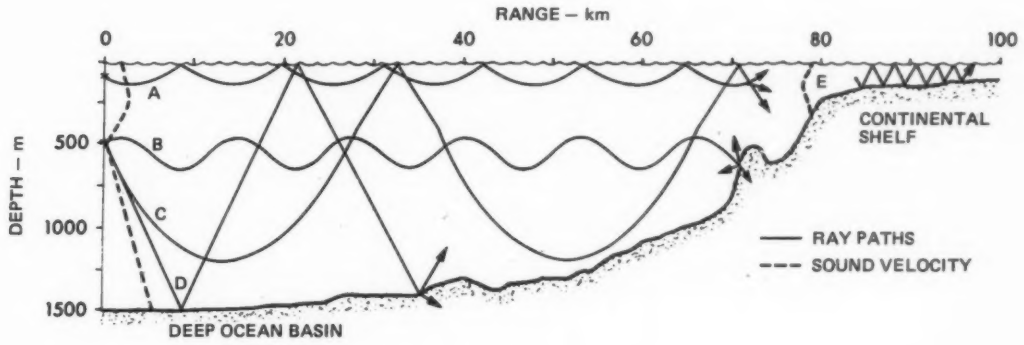


Figure 2

Propagation in shallow water. A tone burst, transmitted in a large beam, initially radiates spherically, with significant propagation into the bottom for rays beyond the critical grazing angle. At longer ranges, internally reflected rays interfere, causing wild fluctuations in the pulse envelope. Finally, a series of modes is established in the shallow water waveguide, with attendant bottom losses and dispersion that cause pulse elongation.

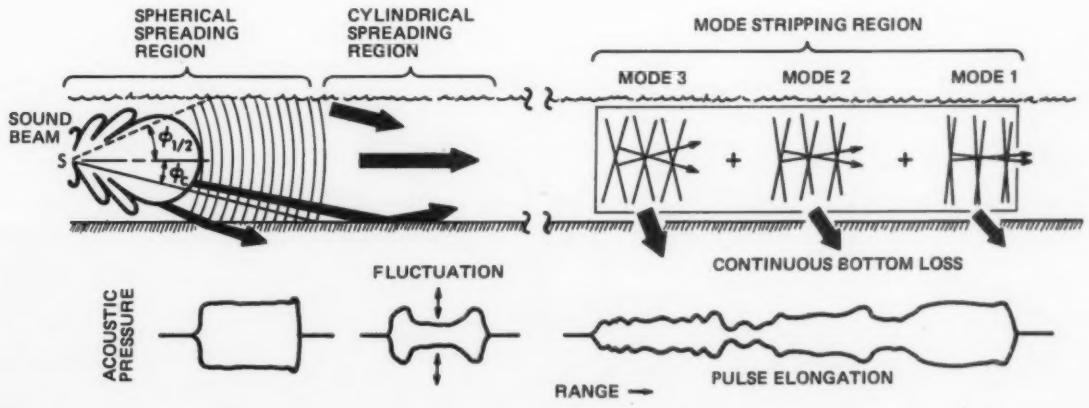


Figure 3

A shallow water acoustics experiment. Up to now, most low frequency measurements have been made with explosive shot sources. This experiment, done at the SACLANT ASW Centre, delineates propagation loss contours, and identifies the optimum frequency (OPF) as a function of range.

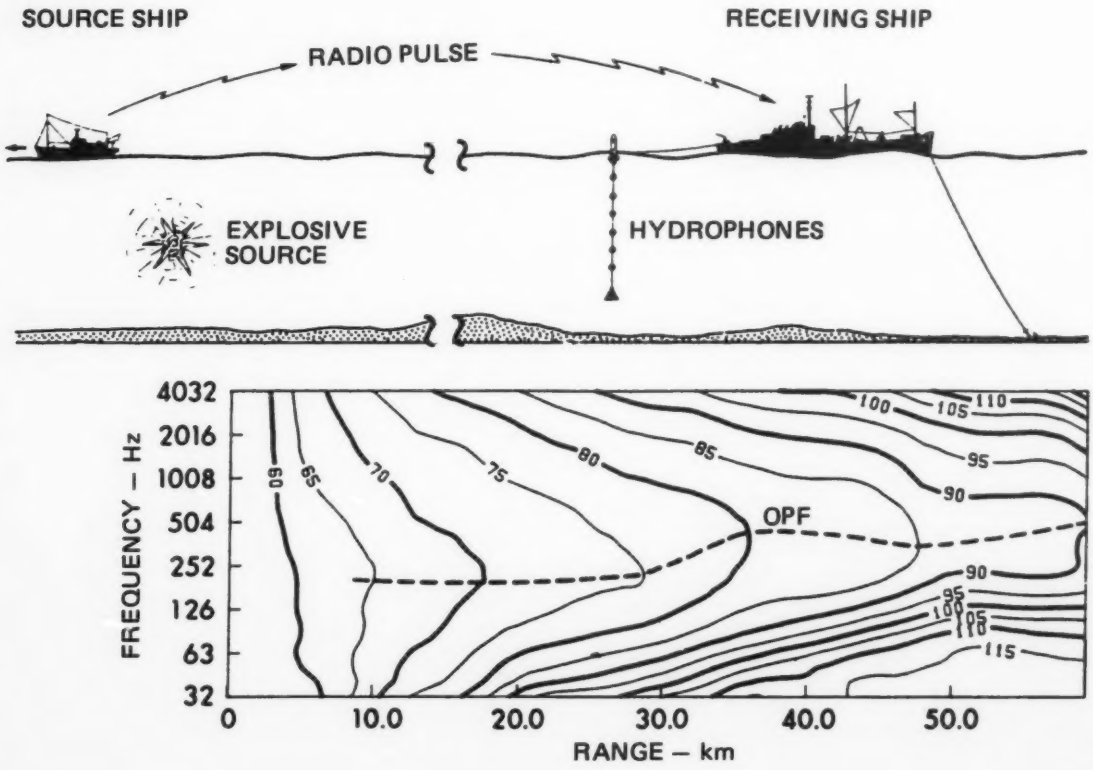
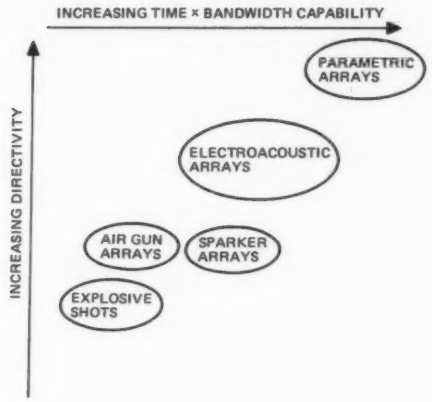


Figure 4

Research tool spectra. Explosive shots are inexpensive and easy to deploy. Experiments requiring directivity and a coherent time-bandwidth product require more sophisticated research tools.



and difficult to construct at low operating frequencies. Parametric arrays offer the highest directivity and bandwidth, even though they are inefficient and are limited to only moderate source levels.

Parametric Arrays

One creates a parametric array (Figure 5) by radiating two high frequency sounds in a narrow beam. The two high frequencies interact nonlinearly in the water, producing a low frequency radiation also having high directivity. The low frequency tone is radiated at the difference of the two primary radiations. Since there is a bandwidth translation from primary to difference frequency radiations, the parametric array has a wide bandwidth capability. Large time-bandwidth products are achieved by transmitting long pulses of wide bandwidth sound. Highly directive, wideband transients can also be created.

Figure 5

Professor Westervelt explains his parametric array. While on a Brown University assignment at the ONR London Office during the 1950's, Peter Westervelt met CAPT Round, a retired Royal Navy scientist who dabbled with transducers in his flat. By accident, one of CAPT Round's experiments produced some curious, highly directive sounds. Westervelt developed the theory for the phenomenon that launched an acoustic discipline and technology of its own.

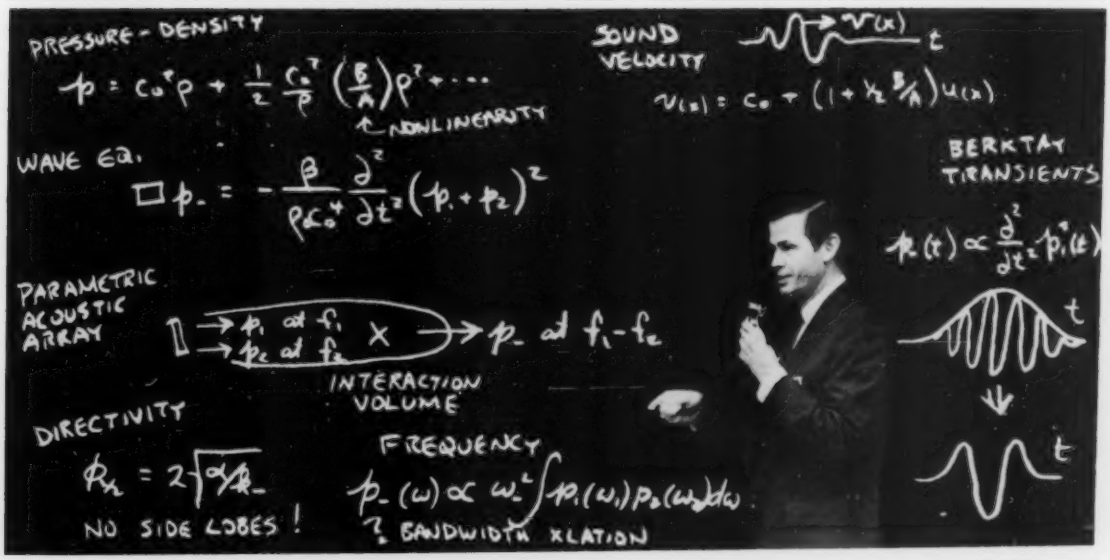


Figure 6

A large transducer used to generate a parametric acoustic array at Applied Research Laboratories, The University of Texas at Austin. This parametic source pumps 80 kW of electrical power into an electroacoustic array of 720 elements, arranged in a circular design, 2.3 m in diameter. With primary frequencies in the 10–15 kHz band and difference frequencies of 1–5 kHz, this research tool develops sufficient acoustic source level to perform a wide variety of shallow water experiments conducted for the Office of Naval Research.

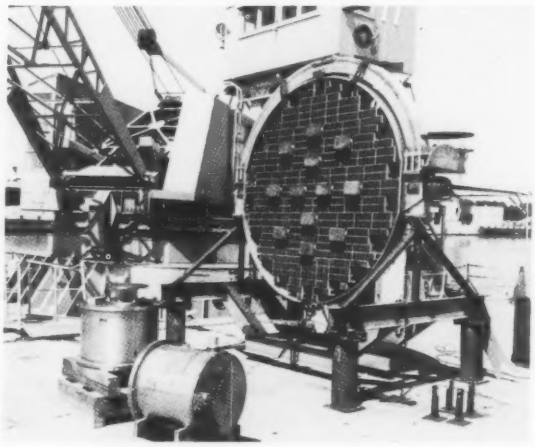
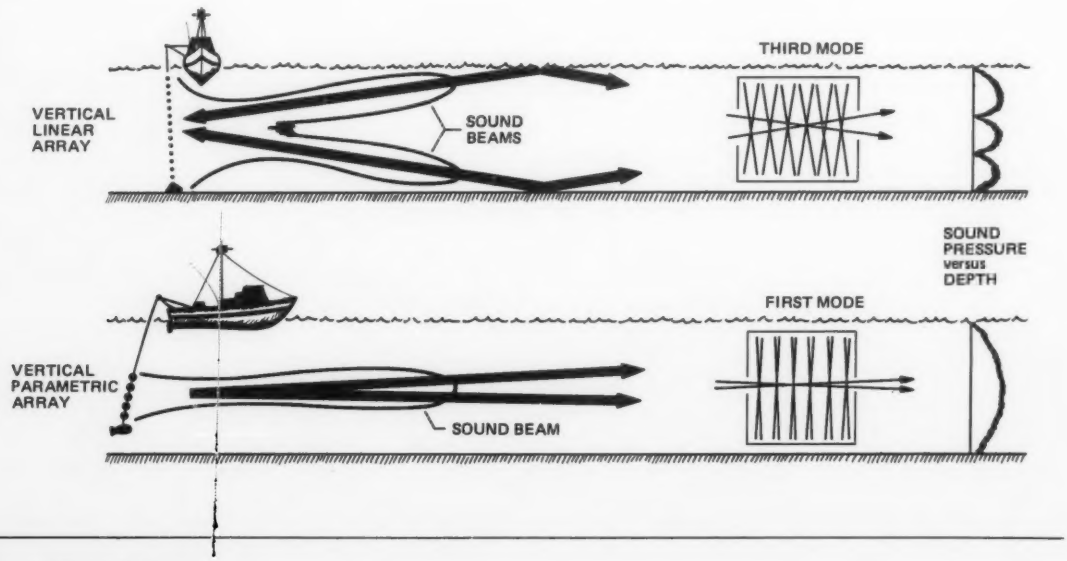


Figure 7

Mode selection in shallow water. With directivity, one can select modes for transmission and reception. Directivity eliminates intermodal interference and considerably improves signal quality. The linear array approach was pioneered by the Naval Research Laboratory while the parametric array technique arose from Office of Naval Research research at Applied Research Laboratories, The University of Texas at Austin.



We have developed a series of parametric research tools for ONR projects over the past 12 years.[3,4] Each successive array has grown larger, more powerful, and capable of operating at lower frequencies (Figure 6).

Mode Selection

One of the first applications of parametric research tools in shallow water was in mode selection[3,5] (Figure 7). Here, a narrow parametric beam was designed to encompass only the angle vectors of the lowest mode. This forced all of the transmitted energy into that mode, which propagated in a clean band of insonification down the waveguide, with none of the fluctuation symptoms of intermodal interference.

This experiment was an extention of a previous experiment done by the Naval Research Laboratory with a vertical linear array in the Gulf of Mexico.[6,7] The linear array experiment can, in principle, excite as well as receive modes, although it is more easily implemented for reception.

It is likely that both linear and parametric mode selection techniques will find further useful application in shallow water reseach. The problem of modal redistribution at the target, for example, could be examined by excitation with a single parametric mode, followed by the reception and partition of modes with a vertical array.

Acoustic Backscattering

One of the most precise measurements that parametic arrays bring to shallow water acoustics are those involving the backscattering of sound from the ocean boundaries (Figure 8), and the volume scatterers lying between them. The illustrated experiment[8] utilized the aforementioned research tool (Figure 6) over the small continental shelf off the coast of Southern California. With the narrow beam of the parametric array, which has no sidelobes, it was easy to isolate the bottom backscattering, as shown. The results show little or no frequency dependence, depending on the interpretation. The measured data taken alone show a slight dependence on frequency (dashed line, 4 dB/decade or frequency to the 1/5 power). When the data are connected to other measurements at higher frequencies[9] (solid line), the interpretation dictates no frequency dependence. This is an exciting result since no theory known to man has predicted such a stable, invariant dependence on frequency. Results like these focus attention on possibilities for new research in sedimentary geophysics because precise measurements on the three-dimensional sediment impedance (density x sound velocity) will be the key the theoreticians need to unravel the backscattering mystery.

Figure 8

Bottom backscattering measurements in shallow water. The parametric array experiment (top portion of figure) yielded useful data over the desired ray path SAS, at a grazing angle of only 10°. The linear experiment (lower portion of figure) was conducted with an electroacoustic array. It was not successful due to the existence of interfering signals in the ray paths SBCS and SDEDES.

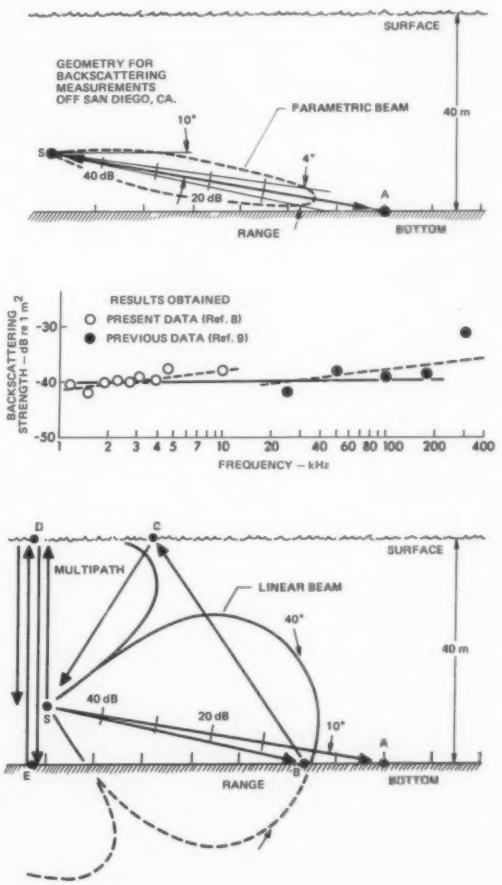
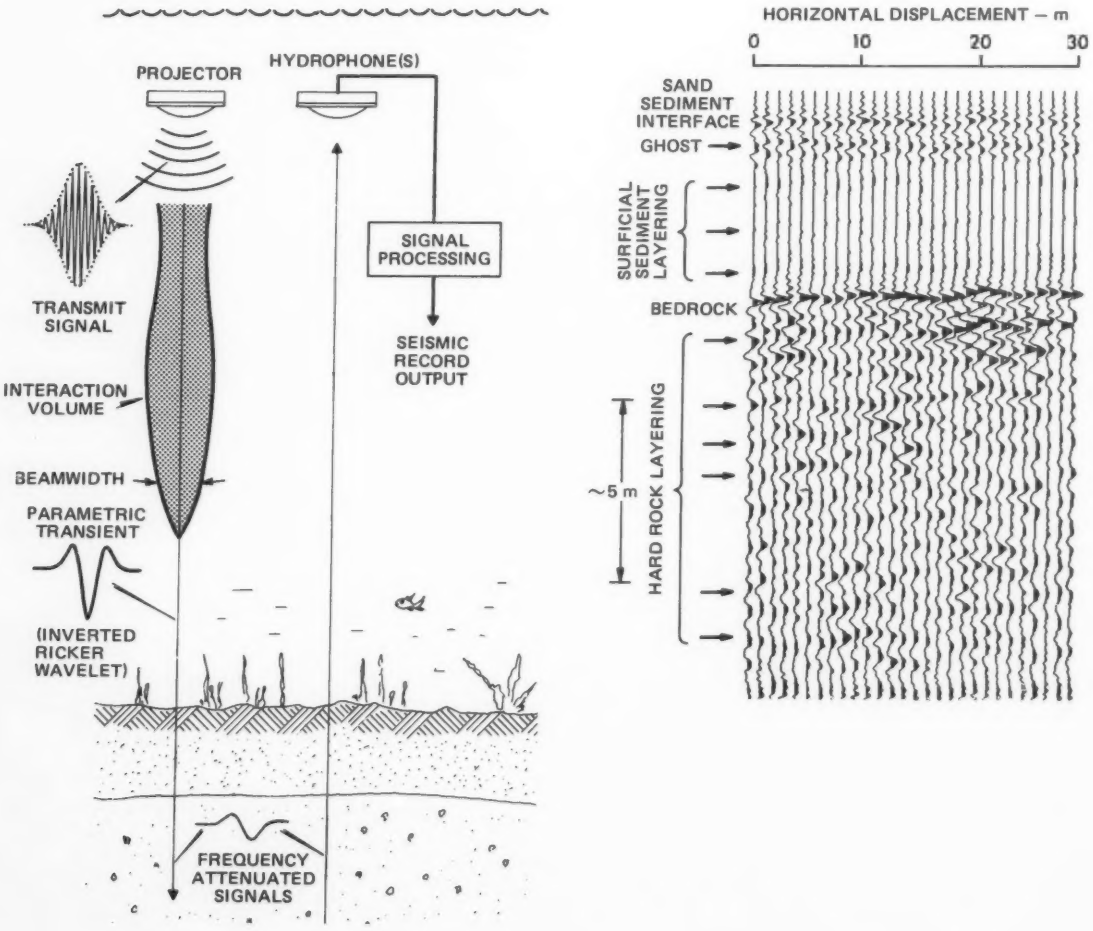


Figure 9

Seismic profiling of the sediments with a parametric transient. A high frequency transmission in the form of a tone burst, modulated in a Gaussian envelope, undergoes a nonlinear demodulation process as it propagates to the bottom. The demodulated waveform, a low frequency, highly directive transient, penetrates the sediment and produces a high resolution seismic record. The data shown here were acquired[8] off San Diego, California, with the research tool of Figure 6.



Complementary to the problem of marking good backscattering measurements is the practical problem of suppressing the reverberation experienced by naval systems. The vertical and near-vertical multipath (Figure 8) can produce a deafening roar over hard bottoms, which can obscure weak sonar echoes. A case can be made for the inclusion of a narrow beam, parametric mode in future sonar systems even though such a mode would be inefficient and would not produce high source levels. This is an attractive possibility because of the existence of signal processing opportunities with wideband parametric signals that could conceivably overcome the inefficiency and produce respectable sonar ranges.

Bottom Profiling

The bottom has long been identified as a major factor in shallow water acoustics, a factor that requires special study. Propagation modeling, for example, requires a knowledge of bottom parameters such as the velocity and attenuation of compressional waves as well as shear waves, the sediment density and sometimes the roughness, all as a function of depth.[1] These parameters are hard to come by and require a tedious combination of core analysis and remote sensing. The difficulty of acquiring sufficient environmental inputs for theoretical modeling may be alleviated in the future as the result of ongoing Office of Naval Research (ONR) research,[10] but some measurements of geoacoustic parameters of the bottom will always be required.

Parametric arrays offer an excellent approach to high resolution profiling of the surficial sediments (Figure 9). Depth resolution measured in fractions of a meter and lateral resolution on the order of a few meters have been demonstrated with this method, which far exceeds the resolution of any known linear system capable of penetrating the sediments. It is interesting to note that the parametric transient waveform (utilized in the data of Figure 9) is an inverted Ricker wavelet. This waveform is widely used in offshore seismic exploration, and is there obtained by filtering the transient signal produced by air guns, which are omnidirectional. We can produce the Ricker wavelet in a highly directional beam by use of parametric transient arrays.

Signal Coherence and Processing

Another critical shallow water experiment, made possible by the ability of directive parametric arrays to isolate scattering mechanisms, is the problem of signal coherence (Figures 10 and 11). For purposes of discussion, let us define a spatially coherent signal as one emanating uniformly from some ideal source or target, while an incoherent signal is the opposite.

Figure 10

The shallow water medium: nature's own "black box" signal convolver. The signal radiated or re-radiated by the target may be spatially coherent or incoherent, depending on the frequency, aspect angle, etc. As this signal propagates through the medium, it is "processed" by bottom interaction, scattering, modal filtering, etc., which alters signal coherence. In the example shown here, the waveforms arriving at the first three elements are spatially coherent and are processed nicely in a linear beamformer. The fourth waveform is dissimilar, while the fifth and sixth are even out of phase with the first three and consequently contribute less to the processing gain that might be expected with a coherent receiver system designed to reject incoherent noise.

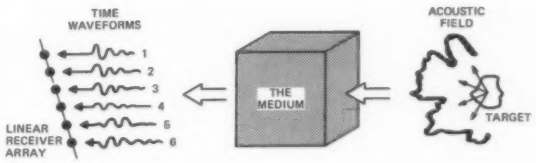
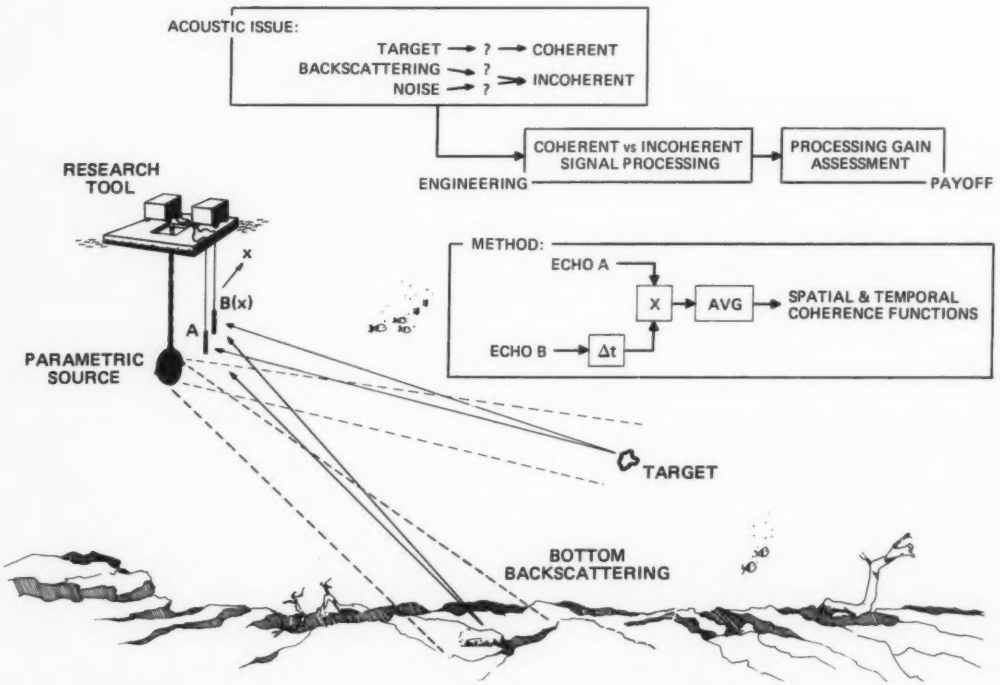


Figure 11

A high resolution spatial coherence experiment. Use of the parametric source of Figure 6 enables the target and bottom scattering mechanisms to be isolated and examined. The coherence of signals received by mutliple hydrophone arrays (only two are shown here) is quantified by utilization of a high speed digital correlator.



Several possibilities exist with intermediate gradations; for example, (1) both the target signature and media effects (i.e., backscattering) result in coherent signals, (2) the target is coherent but the medium is incoherent, (3) the target is incoherent and so is the medium, or (4) the target may be coherent or incoherent and the geophysical and oceanographic properties of the medium continually alter the coherence properties of the signal as it propagates.[11]

Before we conceive or design an experiment or a system, we should determine, or at least estimate, the spatial coherence of the expected signals. This will help us choose the proper size of the acoustic array as well as the type of signal processing we should employ. If, for example, we

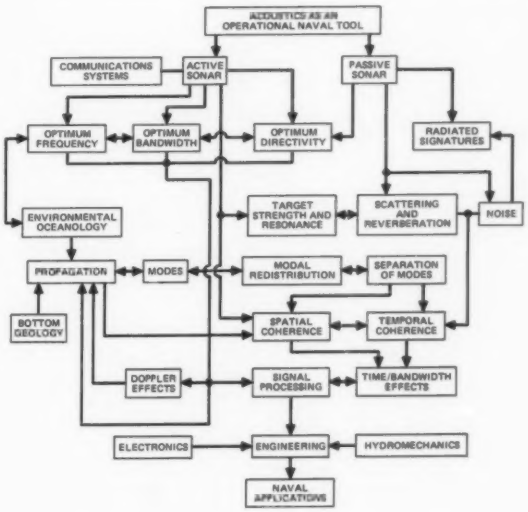
develop a receiving array that is larger than the spatial coherence length of the signal, and try to couple this array to a linear beamformer and/or coherent processor, we will have passed a point of diminishing array gain and performance (Figure 10).

Although the spatial coherence problem is elementary in concept, it is quite difficult to properly account for in underwater acoustic engineering, primarily because of the scarcity of data and knowledge on signal coherence of both the targets and the environment. The research tools and electronic instruments required for the precise measurements needed to characterize and quantify these effects are only now becoming available. In making these measurements, it is important to isolate and examine the various scattering and propagation mechanisms that color the received signal. One such measurement, now being conducted for ONR by ARL/UT Austin at Lake Travis, is designed to separately examine active sonar echoes (Figure 11). Other measurements on passive sonar signals have recently been conducted.

Researchers in both the acoustics and signal processing disciplines are quite excited about the payoffs of coherence studies to sonar technology. On one extreme, we may be able to dispense with hopeless concepts that haven't worked and never will, due simply to the physics of both target and ocean scattering mechanisms. On the other extreme, we should be able to capitalize on new signal processing schemes, especially tailored to our physical limitations, vastly improving the performance of future experiments and systems.

Figure 12

Wiring diagram of critical issues in shallow water acoustics research. As the shallow water story unfolds, these (and many other) topics will be examined both individually and in concert.



The Future

Shallow water acoustics has evolved around the propagation problem, which was instrumental in calling our attention to major differences between deep and shallow water environments.

The propagation problem is an important one, but it is only one of the dozen or so issues facing naval research over the continental shelves (Figure 12). We need to know as much about these other problems as we now know about propagation. It would not be wise, for example, to develop a sonar system at an optimum frequency for propagation if the target or source of interest has no response or signature at that frequency.

At present, researchers worldwide are identifying and investigating new problems peculiar to shallow water and developing them with more experiments, theoretical models, and practical experience. We are seeing increasing application of a wide variety of research tools. New programs for expanded research in shallow water acoustics are being formulated at ONR and elsewhere in the U.S. Navy. Someday, many monographs will be written on the various crucial issues in shallow water acoustics and we may be able to tie this expanded knowledge together to properly deal with the application of naval systems to this environment.

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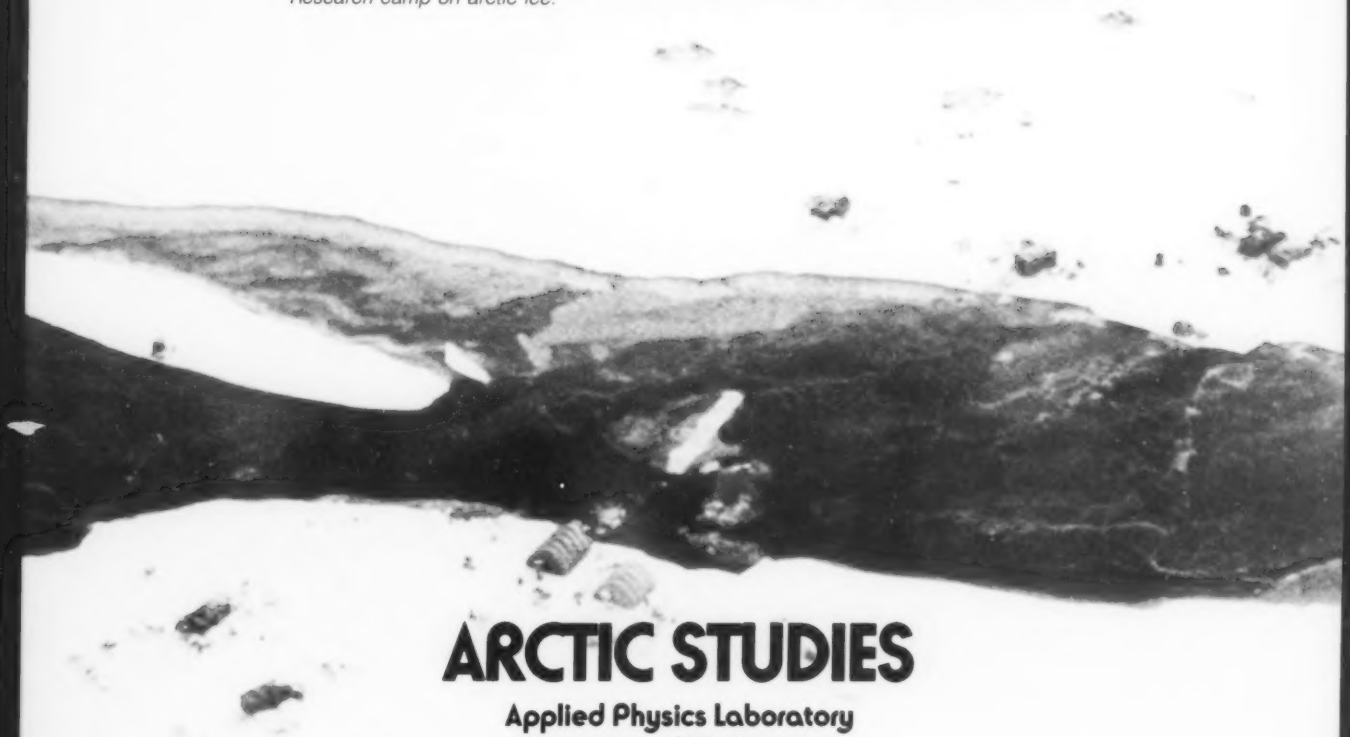
Research camp on arctic ice.



ARCTIC STUDIES

Applied Physics Laboratory
University of Washington

Drifting arctic ice camp divided by large crack in the ice.

The Applied Physics laboratory (APL), University of Washington, has strong research and development capabilities in arctic programs. Two groups within the Laboratory are dedicated to arctic studies, and the work of both is presented in this article. The first, the Polar Science Center (PSC), was formed at the completion of the Arctic Ice Dynamics Joint Experiment (AIDJEX) Project in 1978 to continue the oceanographic and meteorological studies undertaken in the AIDJEX years. When the College of Ocean and [illegible]nces was established by the University in 1981, PSC joined the College as a division of the Applied Physics Laboratory. The second APL unit, referred to as the Arctic Acoustic Research Group, primarily studies acoustics in arctic waters. This work ranges from basic research on all aspects of sound propagation in arctic waters to the testing of sonar and anti-submarine warfare equipment under the ice cover.

DUE TO A LACK OF PHOTOGRAPHIC CONTRAST BETWEEN TEXT AND BACKGROUND, THIS PAGE DID NOT REPRODUCE WELL.

Part One

Polar Science Center

by

Norbert Untersteiner

The work summarized here has its origin in the studies of heat and mass balance of arctic sea ice conducted by the University's Department of Atmospheric Sciences during the International Geophysical Year 1957–1958. This work was carried on in subsequent years with continued support from the Office of Naval Research (ONR) and culminated in the massive effort of the Arctic Ice Dynamics Joint Experiment, which included three pilot studies (1970, 1971, and 1972) and a main experiment lasting from March 1975 to May 1976.[1,2] This work, which is being extended by the Polar Science Center staff (7 scientists, 8 engineers, and 4 administrative personnel) can be roughly subdivided into three categories: theoretical modeling and validation, experiments and data acquisition, and arctic science planning and field support.

Theoretical Modeling and Validation

A concentrated effort, begun in the mid-1960's, has been directed at modeling the growth and decay of sea ice under the influence of heat exchanged with the atmosphere above and the ocean below. A model that incorporated the essential physics[3,4] was used to study the sensitivity of ice thickness to variations of several environmental parameters.[5,6] Suitably simplified versions of this model were used by Maykut[7,8] to study the heat balance and ice production; these models took into account that the arctic ice is not a uniform slab but consists of an ensemble of slabs of different thicknesses.

This thickness distribution was the subject of an important conceptual innovation by Thorndike et al.[9] Their thickness distribution theory relates the fractional area covered by ice of a certain thickness category to both the mechanical and the thermodynamic forcing.

By the mid-1970's, a fairly complete and consistent theory of sea ice behavior had been assembled including as its main ingredients the conservation of momentum, the thermodynamic model, the thickness distribution model, a model relating the deformation of the ice pack to the stresses applied to it, and models relating the applied stresses to the wind and ocean currents. Tests of these ideas were made using the data collected during AIDJEX, which verified some assumptions in the models and left others still unresolved.[10]

Another important result to come from the AIDJEX data was the high correlation observed between the surface wind and the gradient of atmospheric pressure.[11,12] Correlations of greater than 0.95 were observed. This meant that the main driving force on the ice, which is the wind, could be inferred with high accuracy from the most reliable meteorological measurement, the surface pressure. This strong correlation between the surface wind and the pressure field in the Arctic came as a welcome surprise. The correlations at other locations are much lower. In this sense the arctic atmosphere is uniquely well behaved, probably because of the vast uniform lower boundary, the prevailing vertical stability of the air column, and the absence of a diurnal cycle.

A statistical analysis of the pressure field over the Arctic has been carried out by Thorndike.[13] Many properties of the field can be inferred from the observed time-and-space correlation functions for surface pressure. In a sense this study characterizes the mechanical forcing that is available to drive the ice pack.

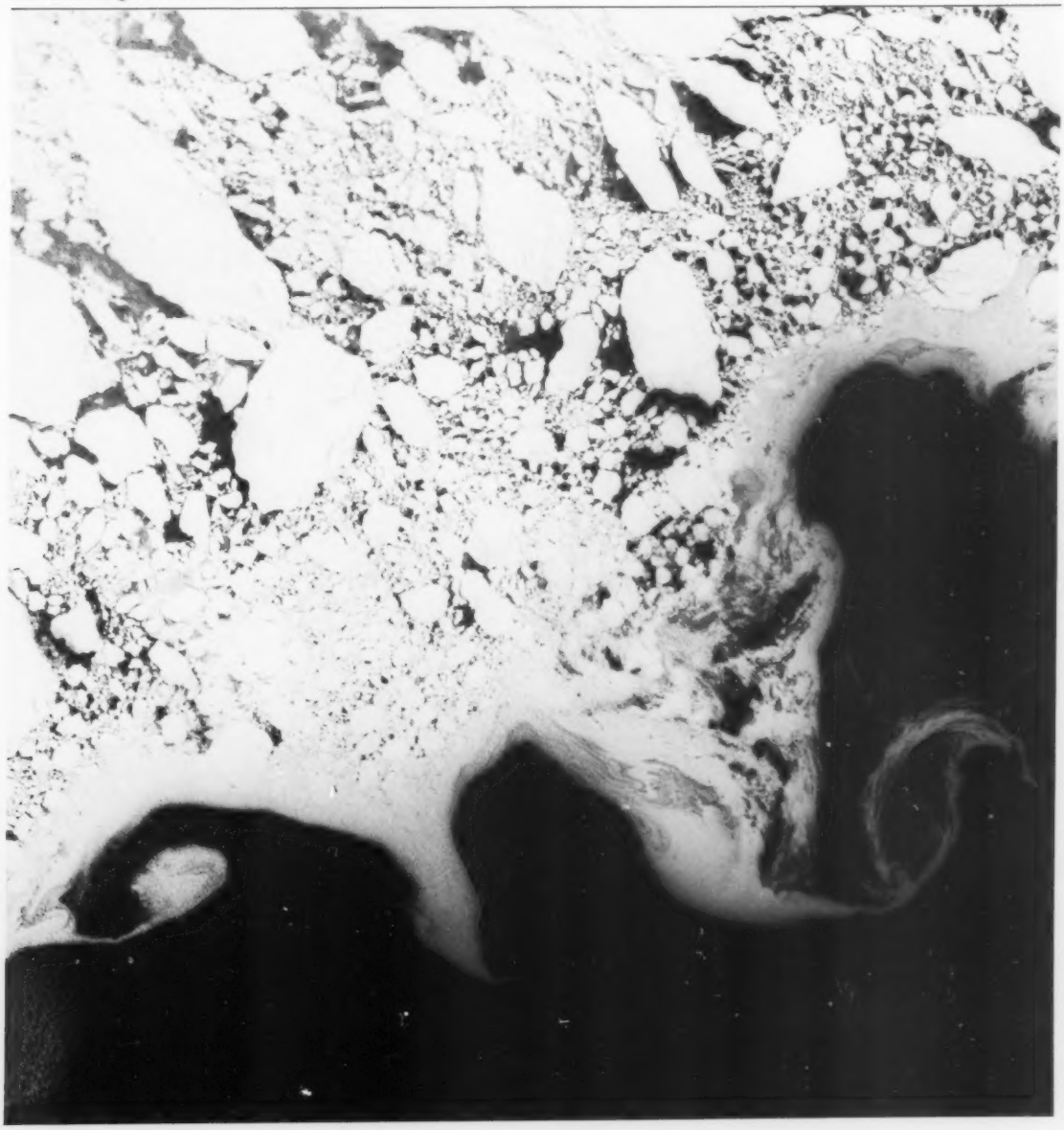
An issue still unresolved by the AIDJEX data is how the bulk mechanical properties of the ice pack depend on the ice geometry. Images of the pack ice at different seasons or in different locations show remarkable variations in the way the ice is broken into discrete floes (Figure 1). A framework for quantifying this aspect of the ice morphology, how it changes in time and is maintained over an annual cycle, and how it affects the behavior of the ice is currently under study. The dynamic importance of the geometry is apparent in the work of Hall and Rothrock, who examined synthetic aperture radar data from SEASAT.[14] In that study, they identified and monitored rigid moving pieces of ice with diameters exceeding 100 km.

Thorndike drew upon these data and data from drifting buoys and manned stations in his 1981 review of sea ice kinematics.[15] He concluded that the movement of sea ice does not vary smoothly from place to place, but is instead extremely irregular, with the actual motions, which occur at the discontinuities between the blocks, having only a weak relationship to the overall flow field. Thus the irregular geometry introduces randomness into the actual field of motion in a way that is not accounted for by present theory.

From a climatic point of view it is desirable to study the behavior of the ice pack over the entire Arctic Ocean. The measurements at drifting buoys, described in the next section, were initiated with this objective. The success of this program derives in part from the strong connection between the pressure field and the surface wind. Thorndike and Colony have used these measurements to see how much of the ice

Figure 1

LANDSAT image of the Greenland Sea marginal ice zone taken on 10 May 1976. Image size is 180 × 180 km. Note the wide range of floe sizes.



motion can be attributed directly to the winds derived from the pressure field.[16] The result is that about 75% of the ice motion is explained by the wind. If the remaining ice displacement is assigned to the effect of upper ocean currents, the vector field shown in Figure 2 emerges.

The circulation of ice in the central Arctic has a mean motion of about 2 km per day due to the mean wind and ocean current, and a short-term variance several times as large due to transient weather systems. From a climatological point of view, one might consider the transient component to be random. Then one could speak of the probability that a piece of ice at a certain location moves to another location during a specified time. The mean motion and the variance of the random motion can now be estimated using the drift records of many drifting stations and buoys, making it possible to estimate the transition probability between any two locations. These probabilities serve as the basis of a stochastic model for ice motion now under development by Colony. The model will predict such statistics of ice motion as the expected residence times for ice in the Beaufort Sea Gyre or in the Transpolar Drift Stream and the dispersion of pollutants.

Experiments and Data Acquisition

Various configurations of drifting data buoys were developed, tested, and used in the central Arctic Ocean during 1970–76 in the Beaufort Sea.[1] Figure 3 shows the ring of buoys surrounding the AIDJEX manned stations and its total deformation during a 12-month period. After the AIDJEX experiment was completed, the Arctic Data Buoy Program was initiated by a grant from the National Science Foundation in 1978 to continue the use of the data buoys in obtaining information on ice drift. Since 1979, major funding has come from the National Oceanic and Atmospheric Administration, with an additional contribution from ONR. The Norsk Polarinstitutt, Oslo, and Canadian government have also been instrumental in maintaining additional buoys in regions that concern them.[17] The Canadian government has purchased a number of data buoys and provides deployment flights. These joint efforts have contributed valuable assistance and scientific data to the program.

The buoys presently in use consist of fiberglass spheres containing sensors, electronic equipment including transmitter and antenna, and batteries. The internal package rotates freely in all directions and assumes an approximately level position regardless of the attitude of the buoy's hull (Figure 4). The hull measures 62 cm in diameter and weighs 38 kg; therefore, aircraft can carry several without affecting their payload significantly.

The buoys are powered by lithium cells with a capacity sufficient for 12–18 months of operation. The buoy positions are computed to within 500 m from the Doppler shift of the buoy transmission as received from the current Argos system on the near-polar orbiting satellite Tiros N. The main meteorological sensor contained in the buoys is a quartz oscillator pressure sensor. These pressure sensors are particularly desirable because of their long-term stability, lack of hysteresis

Figure 2

Monthly means of the upper ocean current vector for the year 1979 (see scale) derived from the difference between a purely wind-driven ice displacement and the displacement actually observed by means of air-deployed data buoys.[16]

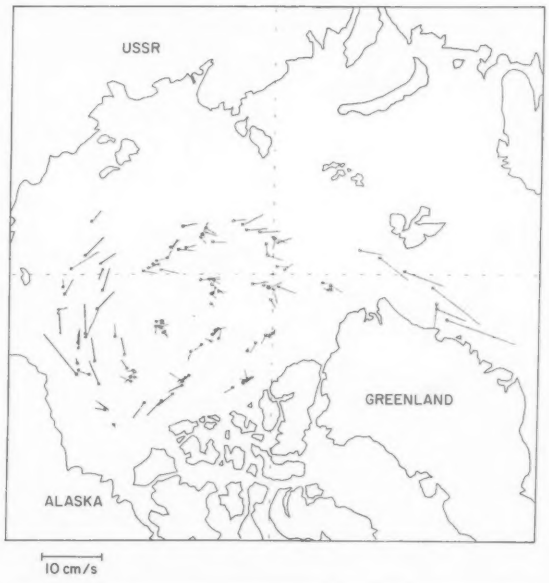


Figure 3

Initial and final positions of the AIDJEX buoy array, June 1975 and May 1976.

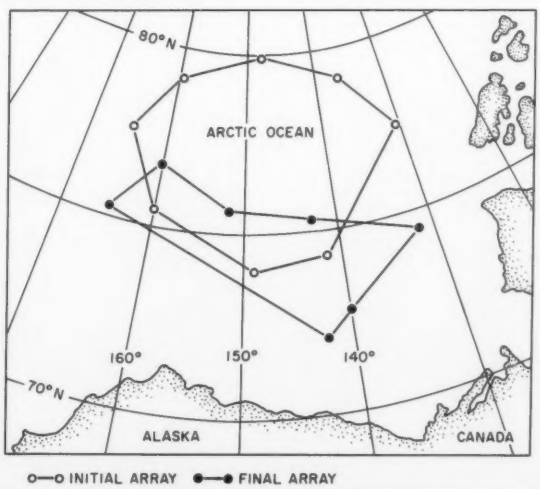
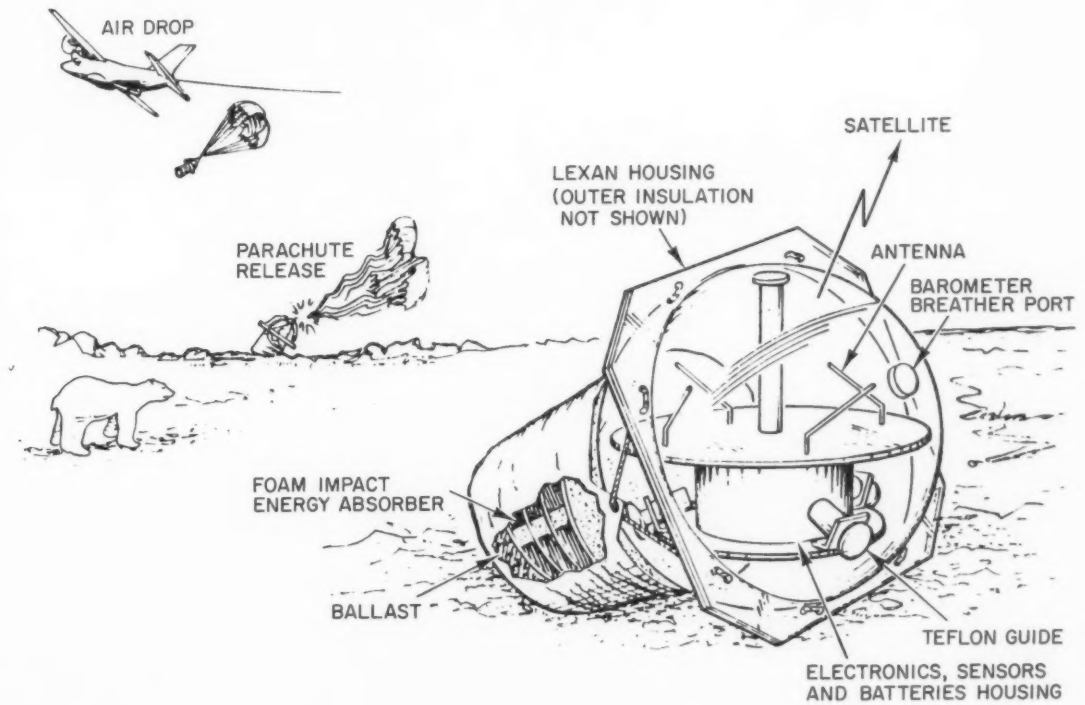


Figure 4

Air-deployable automatic data buoy for use in the Arctic.

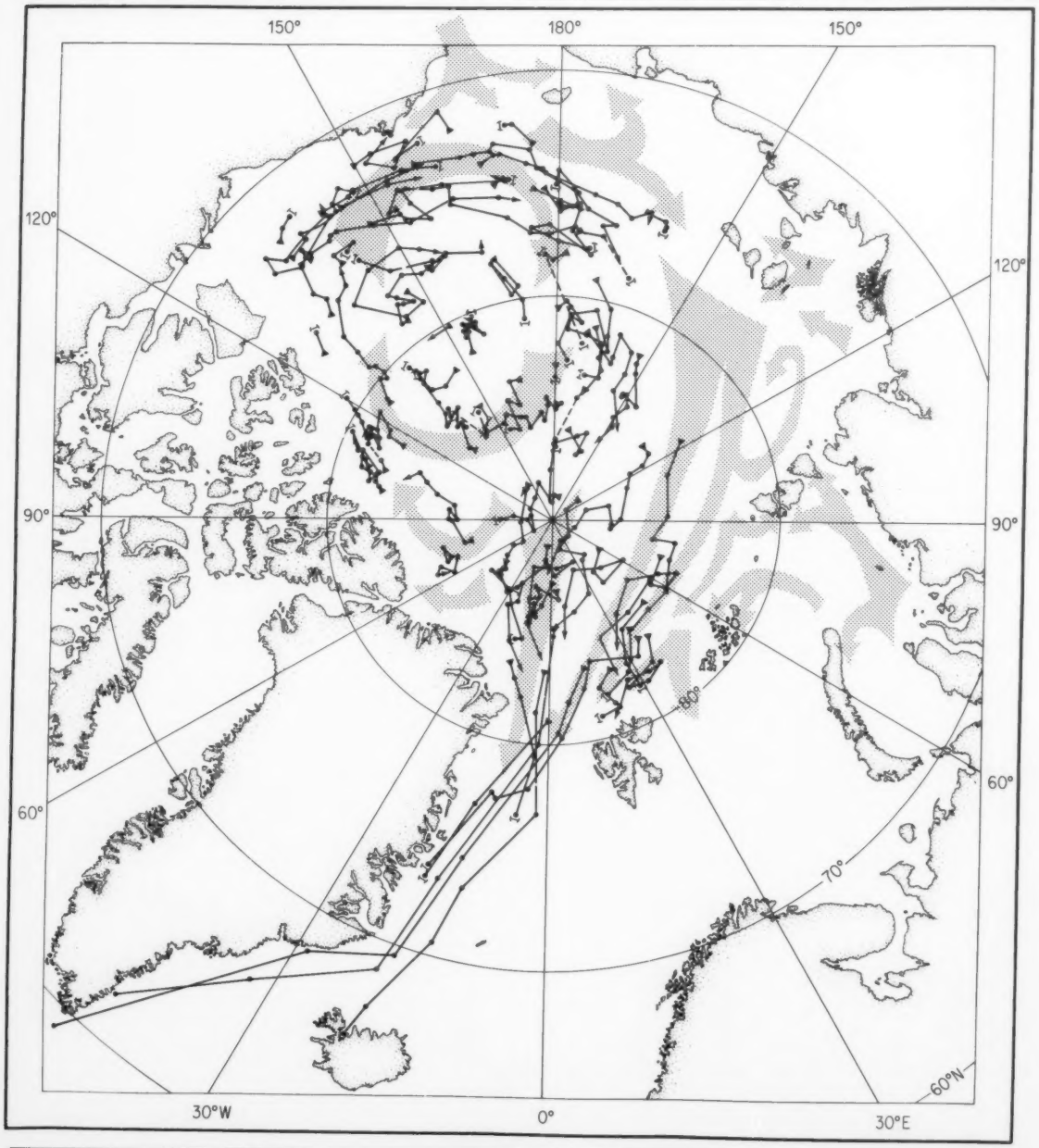


during the large pressure excursions that occur during deployment (drops from up to 3000 m), and low power consumption. The drift rate for the sensors is approximately 0.1 mb per year. The mean service life of 36 buoys in 1979–1981 was 273 days.

Data from the buoys are made available by Service Argos in three ways. They are transmitted directly from buoy to satellite to northern receiving stations (Edmonton, Canada, and Tromsö, Norway) for processing. A second method requires the satellite to transmit stored data from one orbit to receiving stations that relay the data to Toulouse, France, where world-wide distribution of processed data is made over the Global Telecommunications System within three hours of buoy transmission. Third, magnetic tapes containing processed data for one month are mailed during the following month. Final data sets from the arctic buoy network are

Figure 5

Drift paths of 45 air-dropped data buoys between January 1979 and December 1981.[26] The stippled arrows indicate an early estimate of the mean circulation of the upper hundred meters of water in the Arctic Basin.[27]



prepared at the University of Washington for archiving at World Data Center A, Glaciology, in Boulder, Colorado. Cumulative monthly buoy displacements from January 1979 to December 1981 are shown in Figure 5.

Since 1979 data from the arctic buoys have been used by the National Meteorological Center at Suitland, Maryland, for preparing their Northern Hemisphere analyses and forecasts. Several other organizations have public and private responsibilities for local weather and ice forecasting. These include the ice forecasting offices of the National Weather Service in Fairbanks, Alaska, the Atmospheric Environment Service in Edmonton, Alberta, the Navy Fleet Numerical Weather Facility at Monterey, California, and the forecasting units of Dome Petroleum, Shell Oil, and possibly other companies operating in the Beaufort Sea. The data are used routinely by the Norwegian Meteorological Service for their northern European analyses and forecasts, and in support of operations at high latitudes in that sector of the Arctic. For instance, the data were used in support of the Swedish YMER–80 expedition.[18]

Other specialized buoys are also being used to study the uppermost, mixed layer of ice-covered oceans, which are of particular interest because their stratification controls the exchange of heat with the deeper layer and, to some extent, determines the momentum flux (stress) at the underside of the ice. In the Arctic, this layer is 20 to 60 m deep. The arctic mixed layer has been the subject of several field studies by J. Morison. Based on the experience gained at FRAM III[19,20,21] and participation in NORSEX III,[22] Morison's plans for the Marginal Ice Zone Experiment in the Greenland Sea include the use of specially developed temperature-conductivity buoys, a profiling current meter-CTD, and turbulence-measuring current meters to study the mixed layer near the ice edge. Buoys are also being developed that ultimately will remotely monitor seasonal fluctuations in the density structure of the upper ocean of the Eastern Arctic.

Arctic Science Planning and Field Support

As a result of experience gained in numerous field projects, notably the AIDJEX work in 1970–1976, the Polar Science Center has been the prime field support contractor for ONR's arctic field work. These contracts include coordinating the scientific programs of the individual investigators and planning operations, providing field support and communications for remote ice camps, and subcontracting for various services such as aircraft, culinary service, and emergency backup. The most recent activity of this kind has been to support a series of four drifting ice camps called "FRAM I–IV" in the Arctic Ocean north of Fram Strait (Figure 6).

Figure 6

Drift tracks of the FRAM ice camps, 1979–1982.

These camps served as bases of operation for oceanographic, acoustic, and crustal geophysical studies by investigators from the US, Canada, and Norway.[23,19,20]

It has long been recognized that oceanic and atmospheric processes in the marginal ice zone exercise a controlling influence on the entire air-sea-ice system at high latitudes.[24] As a result, after completion of the series of FRAM drifting ice stations, ONR launched the Marginal Ice Zone Experiment (MIZEX) as a new venture that includes numerous specific investigations of oceanic, atmospheric, and ice processes. In collaboration with scientists in Norway, Canada, West Germany, Denmark, Great Britain, and France, field studies began in the Bering Sea in February 1983 and in the Greenland Sea in July 1983. The primary observation platforms for these projects are ships and aircraft. Mr. A. Heiberg of the Polar Science Center is the prime ONR contractor for operations planning and logistics for MIZEX.

Finally, members of the PSC staff are involved in planning, advocating, coordinating, and reviewing research projects and programs, both nationally and internationally. A recently prepared document entitled "Air-Sea-Ice Research Programs for the 1980's"[25] is an effort by scientists from five countries to describe the background and scientific rationale for a comprehensive program including MIZEX and other activities currently under way or being planned.

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Part Two

Arctic Acoustic Research Group

by

Gerald R. Garrison

The Arctic Acoustic Research Group has been involved since 1970 in arctic research under the sponsorship of the Arctic Submarine Laboratory, Naval Ocean Systems Center, San Diego. During the first years, the environment was studied to determine the factors of importance and how they varied with season and location.[1,2] In later years, the effect of the environmental factors on acoustics was examined, at first through the use of propagation measurements under varying conditions[3] and subsequently through the use of components from anti-submarine warfare (ASW) equipment.

Background

Before 1970, most of the oceanographic information about the Arctic came from Nansen bottle casts from icebreakers that cruised there only between late spring and early fall to avoid freezeup. Oceanographic stations were taken along routes selected for other purposes. In 1971, APL's arctic group began a systematic study of oceanographic conditions along the Alaskan coast where a relatively warm current brings Pacific water from the vicinity of Bering Strait. The course of this warm intrusion is along the coast, eventually following the axis of the Barrow Canyon[4,5] which forms a break at the edge of the continental shelf leading into the deep Arctic Basin. At the edge of the intrusion the warm waters interleave with existing near-freezing water to form layered structure and thermal finestructure. Such structure has a drastic effect on acoustic propagation. In 1974, measurements of acoustic transmissions through such waters commenced in an effort to develop relationships between the finestructure and the large acoustic fluctuations that resulted.[3] This study is described in the next section under "Short-Range Acoustic Propagation."

During the same period, another important problem unique to the Arctic was investigated—the acoustic reflections from the ice cover. Under wind stress the ice buckles and forms ridges which, though visibly rugged from above, are many times larger below the surface where less energy is required to displace the blocks of ice downward into "keels" because the ice is only slightly lighter than the water. The ice therefore presents an upper boundary to a sonar's field of view that is unpredictable and greatly different from the often rough but statistically uniform sea surface in warmer climates. This is a problem for the operation of under-ice sonar and ASW systems, which require accurate predictions of acoustic backscattering from the under-ice surface. As a result, considerable research is being conducted to characterize the ice cover and its acoustic properties under various conditions. A description of the treatment of ice reflections is given in the final part of the discussion.

Short-Range Acoustic Propagation

Profile Effects

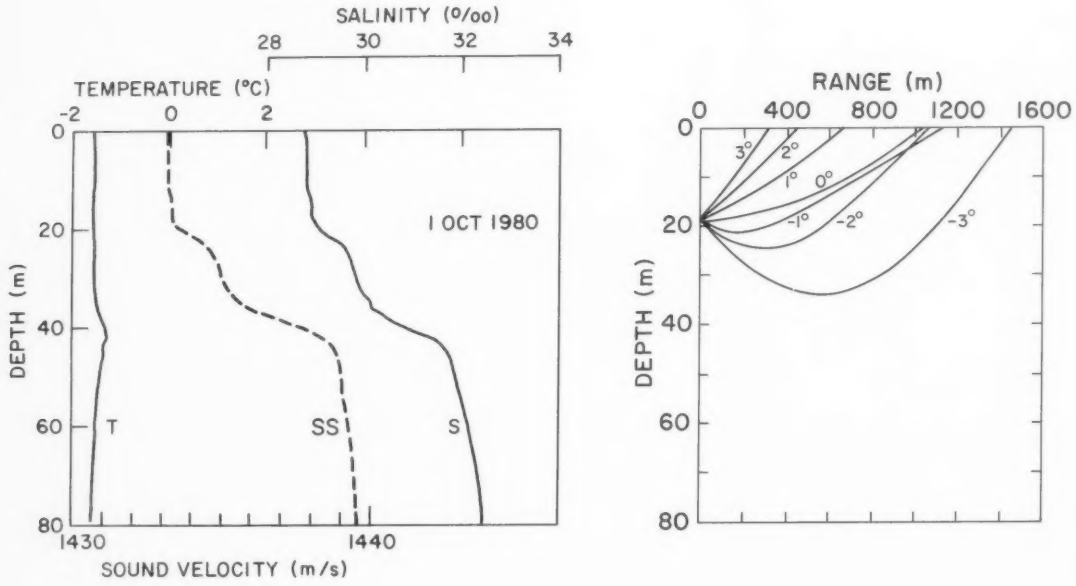
When arctic seas freeze in the winter, the displaced salts sink steadily to lower depths to join a previously formed, high-salinity layer. On the other hand, when the ice melts, the fresh water tends to mix with the lighter surface waters and produce a low-salinity surface layer. The low salinity, in turn, produces a low sound speed, and thus a sound channel is formed near the surface, bounded above by a highly reflective ice cover. A typical sound speed profile is shown in Figure 1a, and the effect on short-range acoustic propagation is shown by the sound ray diagram in Figure 1b. Transmitted sound energy is refracted toward the surface, increasing the ice reflection problem. Along the north coast of Alaska, the warm intrusion, which often interleaves below the surface, disturbs the sound field even further. The effect is so variable that it is not easily predictable. Sound ray diagrams for such conditions show both areas of low intensity called "shadow zones" and areas of high intensity resulting from a convergence of rays. In such cases, the sound intensities may be 10–15 dB above or below normal.

Intensity Fluctuations

In addition to the large variations in sound intensity with depth produced by layers that are appreciable in size and extend along the entire path between source and receiver, there are medium sized variations of intensity that are caused primarily by thermal lenses up to a meter or so thick and tens of meters in horizontal extent. The smallest variations result from the finestructure produced by the partial mixing of intruding layers, by internal waves, and by freezing and thawing processes that tend to separate the salt from seawater.

Figure 1

Typical temperature, salinity, and sound speed profiles for the upper layers in the Arctic, together with a sound ray diagram showing how sound is refracted upward by the profiles.



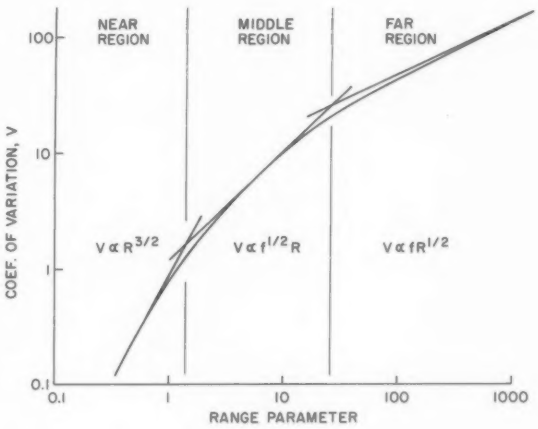
Such finestructure and the associated sound intensity fluctuations must be treated statistically.

Solutions for the sound intensity fluctuations caused by spherical Gaussian inhomogeneities and by oblate spheroidal Gaussian inhomogeneities have been derived by Knollman[6] and Komissarov[7] for both plane and spherical waves. These solutions are unwieldly but are reducible to elementary functions at the short- and long-range asymptotic limits. Schulkin[8] has added a mid-range approximation in which the variations are dependent on the first power of range. The approximate solutions for three range regions are illustrated diagrammatically in Figure 2. Modifications have also been made to extend the solution to anisotropic media.

In 1974 and 1979, we measured acoustic fluctuations with depth in the Arctic at five frequencies (10–75 kHz) simultaneously and at several ranges (200–1200 m) and compared the results with theory. After excluding the effect of the extensive layers, we found that the variations depended on frequency as predicted for the middle region; i.e., $V \propto f^{1/2}$. The measurements at different ranges were taken several hours apart, and the prediction that $V \propto R$ was not so well demonstrated, perhaps because of changes that occurred during the interval between measurements.

Figure 2

Approximation to the Komissarov-Knollman solution for acoustic fluctuations in a medium of Gaussian correlation spheres. (V = standard deviation of intensity/average intensity.)



Absorption

Predicting the performance of sonars in arctic waters requires knowledge of the energy loss due to chemical absorption at low temperatures. Since laboratory measurements are difficult to perform on near-freezing seawater and high accuracy is desired, absorption measurements at realistic ranges in the ocean are necessary.

The absorption of sound in seawater can be considered as the sum of three contributions:

$$\text{TOTAL ABSORPTION} = \text{PURE WATER ABSORPTION} + \text{MAGNESIUM SULFATE ABSORPTION} + \text{BORIC ACID ABSORPTION.}$$

The absorption in pure water was measured at several frequencies many years ago and is well accepted as dependent on temperature and proportional to the square of the frequency, f.

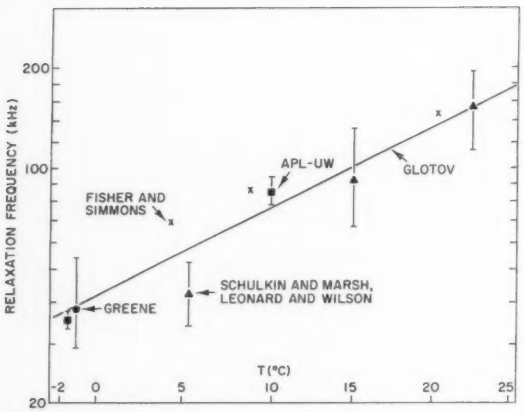
At frequencies of 10-100 kHz a relaxation process involving magnesium sulfate is the primary cause of absorption. Using the nomenclature of Francois and Garrison,[9]

$$\text{MgSO}_4 \text{ ABSORPTION} = \frac{A_2 f_2 f^2}{f_2^2 + f^2}.$$

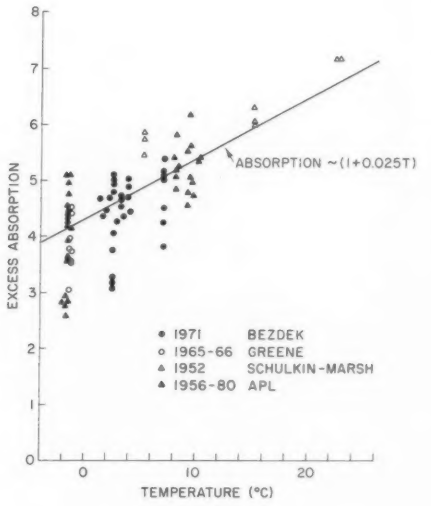
Magnesium sulfate has its maximum effect near its relaxation frequency, f_2, which we have found to decrease as the temperature nears the freezing point (-1.63°C for seawater with a salinity of 30 parts per thousand).

Figure 3

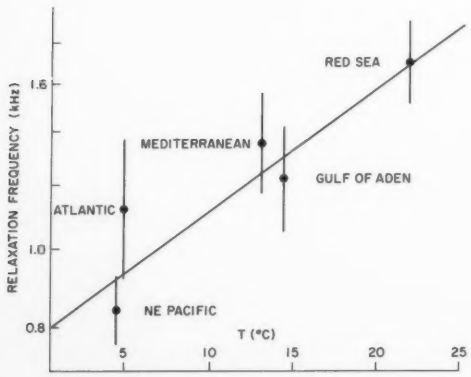
Parameters for the absorption of sound in seawater as determined from ocean measurements. The symbol c is for the speed of sound.[9]



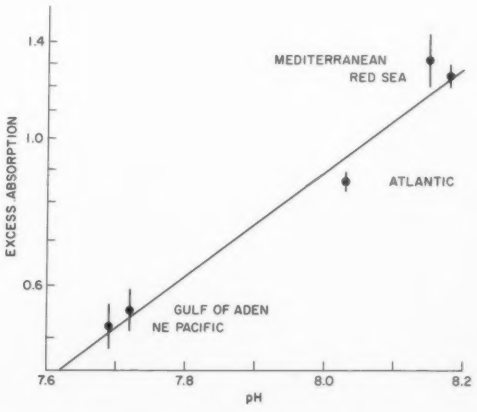
a. $MgSO_4$ relaxation frequency, f_2



b. $MgSO_4$ parameter $A_2 \times c$



c. Boric acid relaxation frequency, f_1



d. Boric acid parameter $A_1 \times c$

Our arctic measurements during the years 1974 to 1980 have shown a greater decrease in relaxation frequency at very low temperatures (Figure 3a) than expected from earlier laboratory measurements that did not extend to such low temperatures (Fisher and Simmons in Figure 3a). A temperature dependence in addition to that for the relaxation frequency is indicated by the absorption measurements of several arctic investigators shown in Figure 3b.[9]

At frequencies below 10 kHz, the relaxation process due to boric acid dominates.

$$\text{BORIC ACID ABSORPTION} = \frac{A_1 f_1 f^2}{f_1^2 + f^2}.$$

For the analysis of ocean measurements at 1–10 kHz, the magnesium sulfate and pure water components must be accurately subtracted to arrive at the boric acid contribution. With a more accurately determined magnesium sulfate contribution, we were better able to determine the boric acid contribution and relate it to temperature and pH. Figure 3c shows the dependence of the relaxation frequency on temperature. Figure 3d shows the dependence of absorption on pH.

When the high-frequency and low-frequency analyses were combined, we obtained the absorption dependence on frequency and temperature diagrammed in Figure 4.[9]

Reflections from Ice

Uniform Ice

When water in the Arctic freezes under quiet conditions, the thickness of the resulting ice is uniform over large areas. The undersurface, however, is rough from the formation of ice crystals and the displacement of salt. The size of the crystals depends on the water movement and the temperature of the air above. Reflections from these uniform areas have been measured at several locations in the Arctic in different years. Surface scattering coefficients have been determined in a manner similar to that used for surface reverberation in the open ocean. The dependence on grazing angle (the angle between the horizontal surface and the sound path) is shown in Figure 5 and compared with ocean reverberation at several wind speeds. Eventually, these uniform areas are usually broken up by wind stresses, and the ridges and piles of ice blocks that result above (Figure 6) and below the ice are the dominant cause of under-ice reflections. However, the backscatter from the uniform surface (Figure 5) may be useful in calculating the reflections from tilted blocks of such ice.

Figure 4

Absorption of sound in seawater and pure water for frequencies of 100 Hz to 1 MHz at three temperatures.

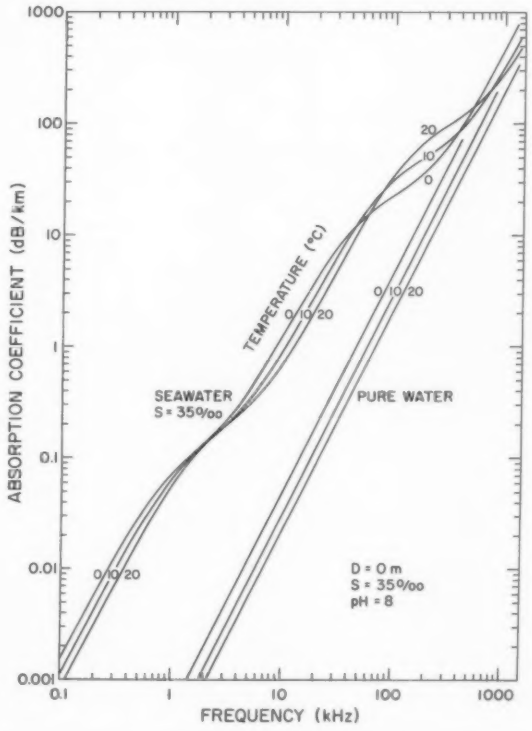
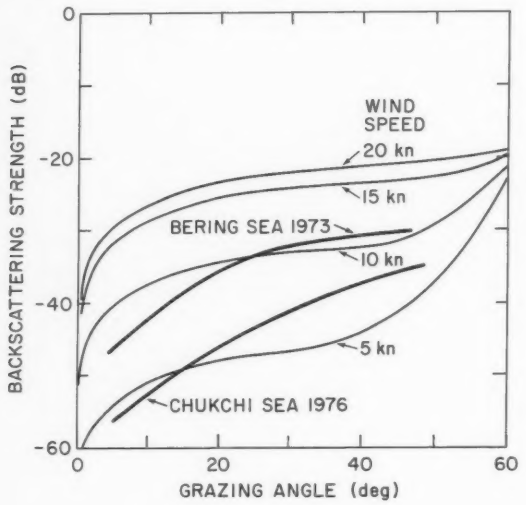


Figure 5

Surface backscattering of unbroken ice compared with that obtained for open water at several wind speeds.



Ice Keels

Observations from above the surface show that generally the ice is severely broken up from wind stress and ice movement. The pressure of one floe against another produces keels of all sizes and shapes. The reflections from these keels are discrete and sometimes similar to those produced by a submarine. The search for a means of separating ice keel echoes from submarine echoes is an important one which will probably continue for some time because of the difficulty of the problem.

Our approach to the study of ice keel reflections is illustrated in Figure 7. Our method has been to suspend a torpedo transducer on a vertical shaft below the ice in such a manner that it could be rotated to scan the undersurface in all directions. This equipment was installed at our ice camp each year, and the returns from all the surrounding ice were measured. The small reflections from the flat ice field were overshadowed by the large returns from the jumbled blocks that make up an ice keel. The target strength of each discrete reflection was determined and compiled into a histogram of ice reflections of various strengths. The results for different areas and seasons varied considerably. The undersurface of the ice varies with season, and in the fall the refractive conditions tend to concentrate the sound at the surface at the range of interest and thus give high target strengths. We are developing methods of characterizing these effects for general use in arctic environmental modeling.

Under-ice profiles by a submarine at slow speed and shallow depth give the most valuable information for estimating the reflections from ice keels because they can detect the steep ice block slopes believed to produce most of the reflections.

Surface Observations

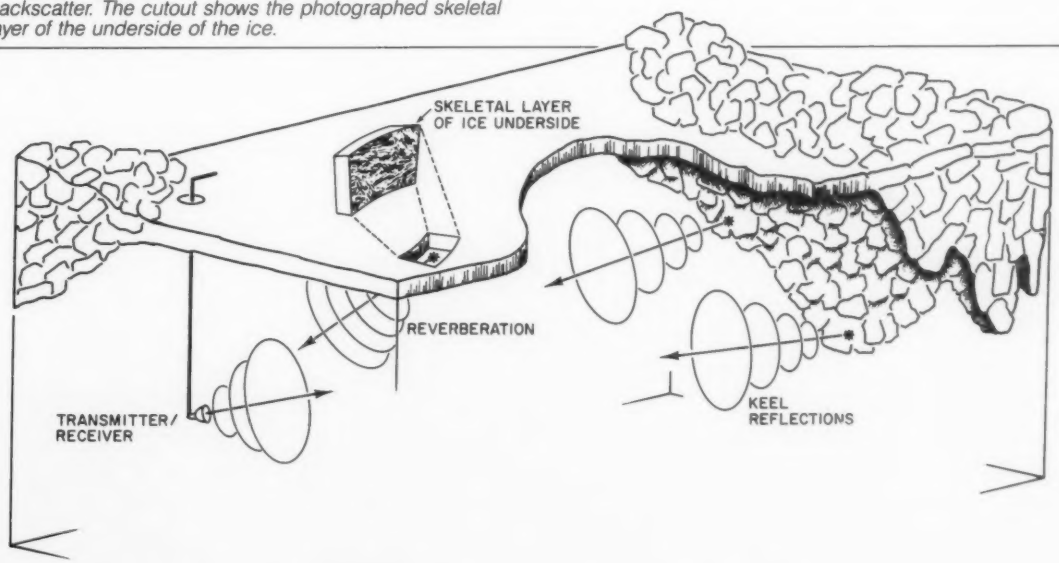
It would be highly desirable to be able to estimate under-ice roughness from surface observations that can be made relatively easily from aircraft or satellite. The surface roughness can be determined from photographs when the sun is at a low angle (as is usually the case in the Arctic). Infrared images and microwave emissions reveal more of the structure of the ice but are difficult to interpret. This science is progressing and may prove very valuable. Another method is the use of laser profilers from aircraft, which give a detailed surface profile along narrow strips. However, after a few months of atmospheric weathering, the correspondence between the roughness seen from above and that existing below is poor, and direct measurements of the underside of the ice are necessary.

Figure 6

A ridge of ice blocks that formed in a few hours near our ice camp. The rifle offers some protection against polar bears.

Figure 7

Diagram of uniform ice and keels showing the transmitter/ receiver arrangement used during measurement of backscatter. The cutout shows the photographed skeletal layer of the underside of the ice.



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Author

Dr. Gerald R. Garrison is a Principal Physicist at the Applied Physics Laboratory, University of Washington. He has been engaged in underwater acoustics research since 1953, with emphasis on arctic acoustic problems since 1970. He has published papers on the mixing of water masses leading to the production of finestructure in the Chukchi Sea on the backscattering of sound from the surface and on the absorption of sound in near-freezing seawater.

Research Notes

Calculation of the Horseshoe Vortex at a Fin-Hull Junction

The proper integration of a propulsor with the hull of an undersea vehicle depends on an accurate knowledge of the detailed flowfield just upstream of the propulsor. Since control fins are present upstream of the propulsor, the flow is necessarily three-dimensional in nature. Two important features of such a flow are the horseshoe vortex that forms at the function of the fin with the hull and proceeds for a long distance downstream and the wake shed by the fin itself. These two features have a significant effect on the propulsor design, but until now such flows could be determined only by experimental means.

With the advent of large and fast digital computers, such as the CRAY, there is hope that the fin-hull flowfield with its horsehoe vortex and wake can be solved numerically. The Applied Research Laboratory and the Mechanical Engineering Department at Penn State, under the New Initiatives Program, of the Office of Naval Research are currently developing a numerical solution procedure for a simplified model of this problem. One of the first tasks, which has already been accomplished, is the generation of a three-dimensional grid network which fits the geometry. At each grid point the flowfield solution consisting of the velocity vector and pressure is then obtained. To properly define the flowfield a minimum of some 50,000 grid points are required.

Although initial calculations will be of hypothetical laminar flows to check that the solution procedure is working properly, the ultimate objective will be to include the effects of turbulence (seemingly random motions) which dominate the horseshoe vortex and wake. Turbulent flows are so complicated that, except in only the very simplest cases, they are beyond the capabilities of numerical solution on present day computers. The alternative is to model the turbulent velocity and pressure fields as the sum of a stationary and a random part. Then, plausible assumptions are made about time averages of products (due to nonlinearity) of the random portion. This procedure will be used in the present problem and use will be made of high quality experiments to determine what the proper modeling hypotheses should be.

Sea-Surface Backscatter

The performance of many high-frequency acoustic systems operating under water is severely limited by backscatter or reverberation from the sea surface. Characterizing reverberation and its relationship to the dynamical properties of the upper ocean is important both for the optimum deployment of existing high-frequency systems and the evaluation of emerging signal processing concepts.

Drs. S.T. McDaniel, A.D. Gorman, and F.W. Symons at the Applied Research Laboratory of the Pennsylvania State University have recently completed an ONR funded study to develop scattering theories and apply them to assess adaptive signal processing techniques. These studies have firmly established that a layer of subsurface microbubbles is the dominant physical mechanism responsible for sea-surface backscatter at frequencies above 10 kHz. Theoretical predictions of surface backscattering strength using measured bubble populations are in good agreement with acoustic reverberation data. The theory predicts not only the observed dependence on the angle of incidence of the acoustic signal but also the saturation that occurs with increasing wind speed. Backscattering strength has been found to increase steadily with wind speeds up to about 20 knots, and then remains constant, regardless of low great the wind speed becomes.

Analytical relations between the Doppler spread of backscattered signals, caused by wave motion, and the directional wave number spectrum of the ocean surface have been derived and verified by comparison with experimental data. These theoretical predictions have been incorporated into a model that generates representative surface reverberation spectra. Signal processing algorithms have been applied to the spectra to determine the optimum pre-whitening filter for reverberation cancellation. The studies indicate that gains in signal-to-reverberation levels up to 8 dB can be obtained by using adaptive vs conventional processing techniques.

Submersible Dives into Active Volcanoes

Geologists using deep submergence vehicles to study and sample underwater volcanoes, as part of the Office of Naval Research's Marine Geology and Geophysics Program, have recently been rewarded by the discovery of mineral-depositing fumaroles 2000 meters below sea level. Following exploratory dives with DSV TURTLE of the USN Submarine Development Group ONE, Dr. Peter Lonsdale of the Marine Physical Laboratory led a diving expedition with the civilian-operated DSV ALVIN to volcanic seamounts that rise 750 meters above the ocean floor 120 miles south of Baja California. These seamounts are like small Hawaiian volcanoes, with craters on their summits from which lava erupts and flows rather gently down the sides; the high pressure of these depths prevents explosive eruptions caused by expansion of volcanic gasses. Within the crater on the summit of one volcano the divers found piles of lava from which "warm" water (15°C, compared to the ambient 2°C) was issuing. These springs or fumaroles are the result of seawater entering the fractured rock and cooling the products of very recent eruptions. As the water exits, it builds "chimneys" of iron precipitates around the vents.

Another nearby volcano lacked any active fumaroles, but had large chimneys and mounds of sulfide rock, like those that grow around very hot (200–350°C) deep-sea springs. These sulfide deposits, which include rich ores of

copper and zinc, are interpreted as the precipitates from high-temperature discharges that in the geologically recent past cooled a large mass of molten rock within the body of the volcano, not just superficial lava flows. Rapid quenching of the interior of this volcano caused it to become extinct a few thousand years ago.

Previous work with unmanned vehicles and submersibles has explored similar hot springs and mineral deposits along the system of mid-ocean ridges, where continuous volcanic eruptions are occuring. The dives onto isolated volcanic seamounts, which generally have a short period of intense eruption and then become extinct, have extended the studies of these hydrothermal phenomena to another deep-sea environment.

Navy Navigation Satellities Probe Ionosphere During Solar Eclipse

Radio beacons from Navy navigation satellites (NNSS) were monitored at 12 sites across the North American continent during the solar eclipse of 26 Feb·uary 1979. The data were collected by seven American and Canadian agencies coordinated by Applied Research Laboratories, The University of Texas at Austin (ARL/UT) with the support of the Office of Naval Research. Drs. J. Clynch and D. Coco of ARL/UT have analyzed the data to provide a clearer picture of ionospheric dynamics during large scale disturbances. This type of information is useful to DoD and civilian agencies in developing long range communication forecasting procedures.

The NNSS in 1000 km orbit are regularly used for navigation and geodetic purposes. In order to obtain accurate positioning, the satellites must transmit at two frequencies to remove the error due to the retardation of the radio wave of the ionosphere. The ionospheric "error," however, was reconstructed and provided a snapshot of the ionosphere during the satellite passage.

The large volume of data avilable allowed the generation of contour maps of the number of electrons above a point on the earth over an area extending over distances of thousands of kilometers. These maps showed that a sharp electron density gradient formed along the edges of the eclipse umbra track. This gradient had a half-life of about 10 minutes and left considerable turbulence behind for up to an hour after umbra passage.

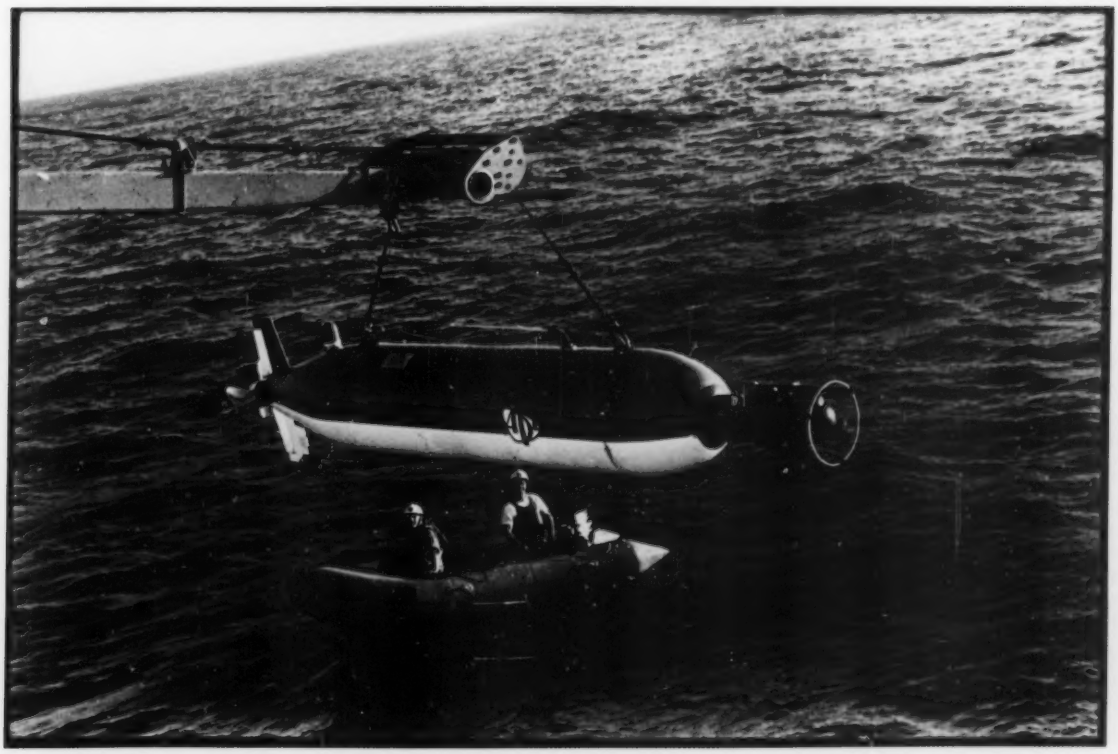
Nearfield of a Large Acoustic Transducer

When an acoustic source emits sound, the amplitude and phase structure of the sound close to the source are very complex due to diffraction effects. This complex structure exists to a range of about d^2/λ (referred to as the "nearfield") from the source where d is the diameter of the source and λ is the wavelength of the emitted sound. In some underwater sound applications, a source is excited simultaneously at two primary frequencies and because the instantaneous localized density of the water is not directly proportional to the acoustic pressure, difference frequency components can be generated. In general, the volume in which the difference frequency components are generated encompasses the nearfield region of the source. Prediction of the difference frequency amplitude and phase within the nearfield and regions beyond involves a detailed knowledge of the nearfield amplitude and phrase structure of the two emitted signals.

Detailed analytical and experimental studies of the nearfield of a large acoustic transducer operating in a linear mode and in a nonlinear mode are now being done. The transducer is 1.82 meters in diameter and operates in the linear mode over the 11–16 kHz frequency range in water. Operating half the elements at one frequency in this band and the other half at another frequency results in the generation of difference frequency sound over the 0.5–5.0 kHz band in the water.

Calculations of the nearfield amplitude and phase within the projected linear beam are based on the parabolic approximation of the Helmholtz equation. Detailed measurements of the amplitude and phase of the projected beam have shown the model to be valid to within a range of $(ka)^{1/3}$ of the plane of the transducer, where a is the radius of the transducer and k is the wave number of the projected sound. This model was then used to calculate the source terms in the equation governing the nonlinear generation of difference frequency sound when two frequencies (primaries) were transmitted simultaneously. The measured nearfield difference frequency amplitude and phase agreed very well with the predicted amplitude and phase because each of the two primary frequency sound fields was described so well by the model. This work is being generalized to include uniform nonuniform amplitude and phase shading of the transducer array.

Drs. Jacqueline Naze Tjøtta and Sigve Tjøtta of Applied Research Laboratories, The University of Texas at Austin (ARL/UT) (on leave from the University of Bergen, Bergen, Norway) have spearheaded the analytical work and Greer Garrett of ARL/UT has supplied the experimental data.



Self Propelled Underwater Research Vehicle (SPURV)

This photo shows deployment preparations for SPURV which was developed by The University of Washington's Applied Physics Laboratory in the early 1960's for oceanographic research. Several versions of this vehicle have been used in ONR-sponsored projects on acoustic propagation and ocean diffusion processes. The acoustically-controlled SPURV can transport sensors through several run geometries at 4–5 kn for 5 hours to a maximum depth of 3000 m.

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